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Assessment of ambient air quality and health risks from vehicular emissions in urban Ghana: A case study of Winneba

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ABSTRACT

Introduction: In Ghana, the road subsector serves as the primary mode of transport, accounting for 96% of passenger and cargo traffic. Air quality issues have been exacerbated by the prevalence of aged and poorly performing vehicular engines, posing significant health risks. This study, therefore, investigated ambient air quality during the dry season along key roadways in Winneba, located in the Central Region of Ghana.

Materials and methods: Stationary monitoring devices, including EPAM-7500 particulate monitors and Aeroqual Series 500 gas monitors were used to measure concentrations of Particulate Matters ($PM_{2.5}$, PM_{10}), Carbon monoxide (CO), Nitrogen Oxides (NO_x), Sulphur dioxide (SO_2), and Volatile Organic C ompound (VOCs) including temperature and relative humidity. Data collection was conducted using a purposive rotation among the selected roads, with each monitoring session replicated three times.

Results: Winneba junction-WindyBay Avenue (WJ'WBA) exhibited the highest concentrations of CO (2125±182.40 μg/m³) whilst the highest level of NO_x (198±27.01 μg/m³) was at Winneba central-Donkorkyiem (WC'D). $PM_{2.5}$ concentrations at WJ'WBA was the lowest (871 ± 79.54 μg/m³), while the Control Road (CR) had highest mean concentration of 902 ± 107.16 μg/m³. The PM_{10} highest mean level was at WJ'WBA (931±51.29 μg/m³) and lowest at the CR (874±90.42 μg/m³). Levels of SO_2 and VOCs were below the detection limits of the gas monitors. In all, levels of the measured pollutants did not differ significantly ($p<0.05$) between the sampling locations, but exceeded the pollution thresholds established by the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA). All monitored roads were classified as "extremely polluted" based on the Air Quality Index (AQI). The Exceedance Factors (EF) confirmed the severity of pollution levels. Statistical analyses, correlation and regression methods, indicated no significant relationship between weather conditions and air pollution levels.

Conclusion: These findings underscore the severity of air quality issues in Winneba and the urgent need for enhanced monitoring systems including the implementation of regular vehicular emission testing and the use of bioindicators for monitoring vehicular pollutants to mitigate both human and environmental health risks.

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Introduction

The global population has steadily increased in recent years, rising from 7.4 billion in 2016 to 7.9 billion in 2021; with projections indicating a potential growth to 9.9 billion by 2050 [1]. According to the World Health Organization (WHO), approximately 90% of the global population resides in areas where air quality fails to meet recommended standards [2]. This surge in population has spurred rapid urbanization, industrialization, and increased commercial activities to meet the escalating demands of societies [1]. A notable consequence of these trends is the rising transportation demand, particularly in regions with underdeveloped public transport systems. This has resulted in a significant reliance on private vehicles, which have become a primary contributor to air pollution worldwide [3].

Vehicular emissions, particularly in developing nations and emerging economies, are a major source of global air pollution [4-7]. In Africa, premature deaths linked to air pollution were estimated to have cost the continent USD 450 billion in 2013, while in Ghana alone, a projected 1.6 billion US dollars are been lost economically each year, thus underscoring the urgent need for comprehensive policy reforms to avert further economic and health consequences [8-10]. Air pollution from vehicular sources has been linked to a range of adverse health effects, including respiratory and cardiovascular diseases, reproductive complications, and early mortality [11].

Studies across Africa have identified asthma as the most prevalent health condition linked to vehicular pollution [12] alongside other conditions such as chronic bronchitis, Chronic Obstructive Pulmonary Disease (COPD), and allergic rhinitis [12-15]. Heavy metals, such as Chromium (Cr), frequently detected in areas with heavy traffic, also pose significant risks to ecosystems and human health [16, 17]. In 2019, about 1.1 million deaths were attributed to air pollution, which is Africa's second-leading cause of mortality [18].

In Ghana, studies have identified particulate matter and gaseous emissions [19, 20], from biomass to petroleum fuel consumption and transportation [21] as major drivers of ambient air pollution. Factors such as poorly maintained vehicles, traffic congestion, and outdated engine technologies exacerbate the emission of pollutants, including Particulate Matter (PM), Nitrogen Oxides (NO_x), Sulfur dioxide (SO_2), Carbon monoxide (CO), and Volatile Organic Compounds (VOCs) [5, 22]. These pollutants present serious environmental and public health risks.

Despite global calls for urgent action, air quality management in Africa is constrained by the lack of inadequate monitoring stations and reliable data, impeding effective policy formulation and implementation [23]. A related study has revealed that only 41% of vehicles in Rwanda and 25% of vehicles in Ghana passed the emission tests [8]. Additionally, every diesel vehicle tested in these countries failed the UK's emission test standards [8]. Meanwhile, air quality monitoring by the Environmental Protection Agency in Ghana have largely been limited to Accra and also lacks comprehensive data on VOCs, especially in other regions [24].

Winneba, a rapidly urbanizing city in Ghana, is situated along a heavily trafficked highway; a major road connecting Accra to other cities in the sub-region. The city experiences continuous movement of light and heavy-duty vehicles, resulting in high-speed traffic that exacerbates transportation and environmental challenges, particularly air pollution [25].

Previous studies in Winneba have highlighted significant air quality issues and potential cancer risk [25, 26]. For instance, one study identified the presence of polycyclic aromatic hydrocarbons (PAHs) and $PM_{2.5}$ in ambient air [25], while another attributed PM_{10} pollution at highway intersections to sources such as soil dust, vehicular exhaust, brake and tire wear, and two-stroke engines [26]. However, these studies overlooked critical gaseous emissions and a comparative analysis of vehicular pollution across key highways in the region. This study therefore investigated gaseous pollutants and their exceedance factors and provides a comprehensive comparative analysis of vehicular pollution across three selected key highways in Winneba.

Materials and methods

Description of study area

Winneba, located within 5.3622° N and 0.6299° W is a vibrant fishing town with a population of approximately 113,919 and situated approximately 35 miles west of Accra, the capital city of Ghana. Nestled along the warm tropical waters of the Gulf of Guinea, the town is characterized by rich cultural heritage and economic activities. Winneba experiences both dry and wet seasons. The average yearly temperature is 27.2 ^{o}C, with monthly averages ranging from 26 to 31 ^{o}C. Relative humidity spans 65% in the late afternoon to 95% at night. In the study area, the north-northeast wind direction is most common, and the average wind speed is between 2.2 and 4.4 m/s [27]. The study area is noted for its rapid urbanization and busy roads which forms part of the West Africa highway that connects to other cities, as well as its proximity to Accra, where poor air quality has been reported both recently and over the years [20, 28, 29]. The study area thus experiences high-speed vehicular mobility where light- and heavy-duty vehicles ply the highways for most parts of the day [25]. It is therefore imperative to investigate air pollution and mitigate the health and environmental impacts of vehicular emissions in such a dynamic urban setting.

Air quality monitoring on selected sampling roads

This study assessed ambient diurnal concentrations of the air pollutants: $PM_{2.5}$, PM_{10}, CO, NO_x, SO_2, and VOCs to determine the impact of vehicular emissions in Winneba, Ghana, during the dry season (November to March). Other environmental variables such as temperature and relative humidity were also measured at the sampling locations. The sampling locations and coordinates of the three key highways and a control road selected based on their significance as major roads and the average traffic volume counts within a specified period [30] were: Winneba junction-Windy Bay Avenue (WJ'WBA; Lat. 05º22.649' and Long. 000º38.432'), Winneba junction-Swedru (WJ'S; Lat. 05º23.178' and Long. 000º38.645'), Winneba central-Donkorkyiem (WC'D; Lat. 05º20.929' and Long. 000º37.505') and the Control Road (CR) as UEW-South (Lat. 05º20.316' and Long. 000º37.520'. Vehicular emissions can also be observed in the form of fumes on the selected roads (Fig. 1).

Sampling was carried out daily at three distinct time intervals: morning (6:30 am to 8:30 am), afternoon (12:00 pm to 2:00 pm), and evening (4:00 pm to 6:00 pm). These periods were chosen to reflect typical daily traffic patterns in Winneba, with morning and evening sessions representing peak commuter traffic and the afternoon session capturing moderate midday activity. The time intervals were determined based on detailed observations of vehicular traffic flow patterns at the selected locations, facilitating an assessment of temporal pollution variations.

Stationary monitoring devices, EPAM-7500 particulate monitors and Aeroqual Series 500 gas monitors, were employed for data collection due to their high sensitivity to vehicular pollutants and robust performance in tropical climates [31-33]. These devices provide precise, real-time data, making them particularly effective for assessing air quality in under-monitored regions like Winneba, Ghana. Measurements were taken at a height of approximately 1 meter above ground level to ensure consistency in data acquisition [33]. Although this height is recommended for assessing human exposure [34], it also helped ensure that the pollutants measured originated from vehicular exhaust which are usually positioned less than 1 m above the road surface [35].

Each session followed a rotational schedule across the four monitoring roads, with three replicates recorded per session. One-minute readings were aggregated into two-hour averages, yielding 120 data points per session to capture pollution dynamics effectively during high-traffic periods.

Air quality index (AQI)

The Air Quality Index (AQI) is a standardized method designed to simplify and enhance the interpretability of air quality data by consolidating measured concentrations of ambient air pollutants into a single numerical value. This approach converts the diverse values of various air pollution parameters into a unified index. The AQI achieves this by combining multiple pollutant concentrations through a specific statistical formula. In this study, the quality ratings of these pollutants at the sampling roads were determined using Eq. 1 as outlined by [36]:

$$Q=\frac{V}{V_s}x100 \tag{1}$$

Where, Q = Quality ratings, V = Observed value; Vs = prescribed standard as permissible limit.

The air quality ratings of the four pollutants (PM_{10}, $PM_{2.5}$, CO, and NO_x) were utilized to calculate the AQI by determining their geometric mean. For the monitored air quality with n parameters, the geometric mean (g) of these n quality ratings was calculated as follows (Eq. 2) [36]:

$$g = antilog\left(\frac{log\ a+\log b+\log x}{n}\right) \tag{2}$$

Where g = geometric mean; a, b, x = various air quality rating values; and n = number of air quality rating values, log = logarithm. Therefore, Geometric mean "(g)= (anti log {(QPM_{10}+$QPM_{2.5}$ QCO + QNO_X /4}) " of their quality rating were computed and taken as AQI. The Air quality classes in view of the AQI are shown in Table 1.

Fig. 1. Fumes from vehicular emissions on a road in Winneba

Table 1. Air quality index classes

Air Quality Index	Classes
0-25	Air quality is classified as clean, signifying favourable conditions for public health and minimal environmental impact.
26 – 50	This range indicates light air pollution, which may be acceptable for short-term exposure from a public health perspective. However, consistent exposure within this range could have long-term adverse health implications.
51 – 75	Moderate air pollution levels suggest potential future health risks, particularly for vulnerable populations, including individuals with pre-existing health conditions.
76 – 100	High levels of air pollution in this range indicate significant potential for adverse health effects on both the general population and susceptible groups, requiring attention and mitigation measures.
> 100	This range signifies extreme air pollution, necessitating emergency alerts and immediate interventions to safeguard public health

Source: [37]

Exceedence factor

Exceedance refers to the duration over which the concentration of a pollutant meets or surpasses the acceptable air quality standards. For air quality assessments, exceedance occurs when the observed pollutant concentration exceeds the standard threshold value. Metropolitan areas, characterized by dense vehicular activity and clustered industrial operations within relatively small regions, have historically exhibited higher pollutant concentrations. These cities have been categorized into four distinct groups based on the Exceedance Factor (EF), which is defined as the ratio of the observed mean concentration of a criterion pollutant to its prescribed limit value (Eq. 3) [38].

$$EF = \frac{Observed\ mean\ concentration\ of\ criteria\ pollutants}{Acceptable\ threshold\ of\ pollutant} \quad (3)$$

A pollutant with a high intensity of deterioration in air quality is considered significant if its exceedence factor value is more than one (Table 2).

Table 2. Categorization of air quality based on exceedance

Exceedence	Description
> 1.5	Critical Pollution (C)
1.0 to 1.5	High Pollution (H)
0.5-1.0	Moderate Pollution (M)
<0.5	Low Pollution (L)

Source: [39]

Statistical analysis

A one-way Analysis of Variance (ANOVA) under Tukey-b was performed to indicate differences in air pollutant concentrations among the various roads. Correlation analysis was conducted to examine the relationship between atmospheric air pollutants and meteorological parameters, specifically temperature and relative humidity. The strength of the associations was interpreted based on Cohen's (1988) guidelines, where values between 0.1 and 0.29 indicate low correlation, 0.30 to 0.49 indicate moderate correlation, and 0.50 to 1.0 indicate strong correlation. Multiple regression analysis was carried out to assess the influence of meteorological conditions on air pollution concentrations. All analyses were done using SPSS version 26.

Results and discussion

Ambient air quality analysis of NO$_x$, CO, PM$_{2.5}$ and PM$_{10}$

In Table 3, the concentrations of NO$_x$ had the highest mean value (198±27.01 µg/m^3) at WC'D and the lowest (168±51.93 µg/m^3) at the CR. The NO$_x$ levels were higher than the 24-h WHO limit of 25 µg/m^3, indicating poor air quality in the study area. Statistically, there were no significant differences in the levels of NO$_x$ between the various sampling locations. There was a significant variation in the levels of carbon monoxide; WJ'WBA had the highest mean concentration (2125±182.40 µg/m^3) and the lowest (821±485.87 µg/m^3) at the CR (Table 3).

Regarding PM$_{2.5}$ concentrations, WJ'WBA recorded the lowest mean value of 871 ± 79.54 µg/m^3, while the CR exhibited the highest mean concentration of 902 ± 107.16 µg/m^3 (Table 3). These results reflect poor air quality across all monitored roads, with levels exceeding the WHO limit of 15 µg/m^3 and the USEPA limit of 35 µg/m^3. Although no statistical significant difference in PM$_{2.5}$ levels was observed between the locations, the consistently high concentrations underscore a widespread air pollution issue. For PM$_{10}$, the highest mean concentration was recorded at WJ'WBA (931 ± 51.29 µg/m^3), while the CR had the lowest mean value (874 ± 90.42 µg/m^3) as shown in (Table 3). Similar to PM$_{2.5}$, PM$_{10}$ concentrations were significantly above the recommended standards, and no statistically significant differences were detected across the study locations.

The mean NO_x concentrations ranged from 168±51.93 µg/m³ to 198±27.01 µg/m³ across the study locations. These levels exceed the WHO 24-h guideline of 25 µg/m³ by over 670% to 790%. This is consistent with findings from other urban areas in sub-Saharan Africa, such as Accra, Ghana, and Lagos, Nigeria, where rapid urbanization and vehicular emissions have been identified as significant sources of NO_x [40-42]. For instance, the pollution levels reported in this study were significantly higher than the annual mean values of 68 to 70 µg/m³ documented by [43] on roads in the Accra Metropolis. Similarly, [33] observed NO_x levels of 0.08–0.10 ppm in the Kumasi Metropolis, exceeding expected thresholds. In Lagos, Nigeria, [44] reported higher NO_x concentrations (67.10 µg/m³) during the dry season compared to the wet season (50.16 µg/m³). Consistent with our findings, [45] revealed that residents in Kigali, Rwanda, were exposed to substantial NO_x levels exceeding WHO guidelines. The lack of statistically significant differences between locations suggests that NO_x pollution is ubiquitous, likely due to high vehicular density along key roadways.

The CO concentrations were highest at WJ'WBA (2125±182.40 µg/m³) and lowest at CR (821±485.87 µg/m³). These values significantly exceed the WHO 8-hour guideline of 10,000 µg/m³ when normalized over time, reflecting intense localized pollution. Similar patterns have been reported in congested urban centers in India and China, where high CO levels are attributed to vehicular emissions [46-48]. Although the observed CO levels in this study were higher than the WHO and USEPA limits, they remained below the EPA-Ghana standard of 720,000 µg/m³, demonstrating compliance with local regulations. However, this should not diminish concerns; as such concentrations could still pose health risks depending on the extent of exposure. Interestingly, [44] found higher CO levels during the wet season (10,115.88 µg/m³) compared to the dry season (6,489.47 µg/m³) on some Lagos roads, underscoring the complex interplay of meteorological factors. In Yopougon city, Abidjan, Côte d'Ivoire, [49] identified road traffic as the primary source of emissions, with CO (14.8 t/d) and NO_x (7.9 t/d) being the most prominent pollutants. CO and NO_x are both widely recognized as major traffic pollution tracers.

$PM_{2.5}$ concentrations, ranging from 871±79.54 µg/m³ to 902±107.16 µg/m³, far exceeded the WHO and USEPA limits (15 µg/m³ and 35 µg/m³, respectively). Similarly, PM_{10} concentrations, with mean values between 874±90.42 µg/m³ and 931±51.29 µg/m³, surpassed the WHO 24-h guideline of 50 µg/m³. These results are comparable to levels observed in heavily industrialized regions in South Asia and Africa, where unregulated emissions from vehicles and dust resuspension dominate [50, 51]. In South Africa, about 97.6% of the population was exposed to $PM_{2.5}$ concentrations exceeding the WHO's 2005 recommendation of a 10 µg/m³ annual mean in 2012 [52]. The population-weighted annual average $PM_{2.5}$ levels increased from 26.6 µg/m³ to 29.7 µg/m³ between 2000 and 2012, further highlighting the urgency of addressing air pollution across Africa [52].

The updated 2021 WHO annual PM_{10} guideline of 15 µg/m³ stands in stark contrast to daily PM_{10} concentration trends in Gauteng Province, South Africa, which are 5.7 times higher, even during winter [53]. Controlling vehicle type and speed on paved and unpaved roads has been proposed as a strategy to reduce vehicle dust emissions [54]. However, such mitigation plans require careful review and stakeholder consultation before implementation. Further evidence from [55] highlights alarming air quality pollutants in Kampala and Nairobi, where $PM_{2.5}$ and PM_{10} concentrations frequently exceeded WHO limits, posing significant health risks. In Kampala, roadside concentrations of $PM_{2.5}$ (193%) and PM_{10} (215%) were above WHO thresholds, while urban background levels exceeded limits by 122% and 69% respectively. These findings underscore the need for continuous air quality monitoring across African cities.

This study, conducted during the dry season in Winneba, Ghana, adds to the growing body of evidence suggesting the Sahara Desert as a significant source of PM in the region, particularly during harmattan periods. Seasonal variations in particulate matter levels are well-documented, with increased precipitation and wind speeds generally reducing PM concentrations. However, exceedances of WHO Air Quality Guidelines remain prevalent during the dry season in this region [23].

The exceedance of these standards has profound health implications. Elevated NO_x levels are associated with respiratory and cardiovascular diseases, including asthma exacerbation and reduced lung function [56]. High $PM_{2.5}$ and PM_{10} concentrations pose an even greater risk, as they penetrate deep into the respiratory system, leading to Chronic Obstructive Pulmonary Disease (COPD), lung cancer, and premature mortality [32, 52]. Prolonged exposure to elevated CO concentrations can impair oxygen delivery to tissues, exacerbating cardiovascular conditions. In comparison, cities with stricter emission controls, such as London and Los Angeles, report significantly lower pollutant levels, highlighting the effectiveness of stringent policies like vehicle emission standards and air quality monitoring frameworks [57, 58].

Table 3. General ambient air quality of Winneba major streets

Sampling roads		**NO_X ($\mu g/m^3$)**	**CO ($\mu g/m^3$)**	**$PM_{2.5}$ ($\mu g/m^3$)**	**PM_{10} ($\mu g/m^3$)**	**Temperature**	**Relative humidity**
WJ'WBA	Min	50	0	83	490	27	65
	Max	414	23700	1160	1090	32	89
	Mean	185±95.73 ^{a}	2125±182.40 ^{a}	871± 79.54^a	931±51.29^a	29.67±2.52	75.67±12.22
WJ'S	Min	67	100	610	320	28	66
	Max	302	6100	1040	1300	32	86
	Mean	181±87.88 ^{a}	1783± 780.25 ^{a}	877± 82.53^a	875±53.79^a	30.33±2.082	73.67±10.79
WC'D	Min	131	100	750	460	26	66
	Max	265	7300	1030	1020	32	90
	Mean	198±27.01 ^{a}	1804± 792.43 ^{a}	879± 81.80^a	884±15.04^a	29.33±3.055	75.33±12.86
CR	Min	22	0	630	580	27	66
	Max	930	5000	1530	2890	32	88
	Mean	168±51.926 ^{a}	821± 485.87 ^{a}	902±107.16^a	874±90.42^a	30.33±2.88	74.33±11.93
Standards							
WHO/24 h		25 $\mu g/m^3$	7 $\mu g/m^3$	15.0 $\mu g/m^3$	45.0 $\mu g/m^3$		
USEPA/24 h		25 $\mu g/m^3$	35 $\mu g/m^3$	35 µg/m3	150 $\mu g/m^3$		
EPA-GHANA/24 h		150 $\mu g/m^3$	720000 $\mu g/m^3$	35 µg/m3	70 $\mu g/m^3$		

Mean ± SE in the same column with different letters in superscript are significantly different ($P \leq 0.05$)

WHO: World Health Organization [56]; USEPA: United States Environmental Protection Agency [32]; EPA-Ghana: Ghana Environmental Protection Agency [59]; N/A: Not available

Air quality rating using AQI

Table 4 summarizes the air pollution index across the various sampling locations in Winneba, Ghana, based on pollutant concentrations. WJ'WBA recorded the highest pollutant levels: with NO_x (740 µg/m³), CO (6071 µg/m³), $PM_{2.5}$ (2488 µg/m³), and PM_{10} (620.6 µg/m³) resulting in an AQI of 1622.89, categorizing it as "Extremely Polluted". Similarly, WJ'S and WC'D exhibited high pollution levels, with AQIs of 1523.61 and 1567.70 respectively. The CR also showed severe pollution, with an AQI of 1240.22, indicating the "Extremely Polluted" status.

All monitored locations revealed critical air quality issues, likely driven by vehicular emissions. Similarly, AQI values on major roads in Ghana, such as Kumasi-Accra (154.24), Kumasi-Offinso (143.76), and Kumasi-Mampong (147.34), also indicated severe pollution [33]. In comparison to other areas, studies in Senegal [14] reported the highest AQI values in Yoff and HLM at approximately 497 and 488 respectively—significantly lower than those recorded in this study.

Exceedance factor (EF)

The ambient air quality exceedance in Winneba was confirmed using the criteria outlined in Table 2 for each pollutant based on their respective Exceedance Factor (EF) values. NO_x levels ranged from 6.72 at CR to 7.92 at WC'D, all classified as "Critical Pollution" (Table 5), indicating deviation from permissible limits.

CO levels exhibited relatively higher EF values, ranging from 23.46 at the CR to 60.71 at WJ'WBA, further underscoring severe air pollution. Similarly, $PM_{2.5}$ and PM_{10} concentrations were categorized as "Critical Pollution," with $PM_{2.5}$ EF values exceeding 24 and PM_{10} EF values between 5.83 and 6.21. These findings reflect particulate pollution attributable to vehicular emissions.

Contrary to a report by [33], which documented pollution levels ranging from low to severe in the Kumasi Metropolis, this study observed consistently critical pollution across all monitored roads, including the control site. While the control site recorded comparatively lower pollutant concentrations, the values still exceeded the established threshold of <0.5 (Table 2), underlining air quality concerns in the study area.

Table 4. Roadside air pollution index evaluation in Winneba, Ghana

Sampling roads	**Rating of Air Quality using Eq. 2**					**Classification**
	NOx	CO	$PM_{2.5}$	PM_{10}	AQI	
WJ'WBA	740	6071	2488	620.6	1622.89	Extremely polluted
WJ'S	724	5094	2505	583.3	1523.61	Extremely polluted
WC'D	792	5154	2511	589.3	1567.70	Extremely polluted
CR	672	2345	2577	582.6	1240.22	Extremely polluted

Table 5. Exceedance factor (EF) of the monitored ambient air quality parameters

Sampling roads	NO_X	CO	$PM_{2.5}$	PM_{10}
WJ'WBA	7.4 (C)	60.71 (C)	24.89 (C)	6.21 (C)
WJ'S	7.24 (C)	50.94 (C)	25.06 (C)	5.83 (C)
WC'D	7.92 (C)	51.54 (C)	25.11 (C)	5.89 (C)
CR	6.72 (C)	23.46 (C)	25.77 (C)	5.83 (C)

(C) = Critical Pollution; (H) = High Pollution; (M) = Moderate Pollution; (L) = Low Pollution

Correlation between air pollutants and weather conditions

Table 6 presents the associations between air pollutants and weather conditions (temperature and relative humidity) in the study area. The results indicate that CO did not show statistically significant correlations (at $p<0.05$) with any air pollutants or weather conditions. NO_x demonstrated significant negative correlations with $PM_{2.5}$, PM_{10}, and relative humidity, as well as a significant positive correlation with temperature (Table 6). $PM_{2.5}$ exhibited significant negative correlations with NO_x and temperature, and positive correlations with PM_{10} and relative humidity. Similarly, PM_{10} showed significant positive correlations with $PM_{2.5}$ and relative humidity, and significant negative correlations with NO_x and temperature (Table 6). Temperature displayed significant positive correlations with NO_x and negative correlations with $PM_{2.5}$, PM_{10}, and relative humidity. Relative humidity showed significant negative correlations with NO_x, $PM_{2.5}$, PM_{10}, and temperature (Table 6).

In contrast, [33] reported strong positive correlations between CO and SO_2, NO_2, and relative humidity ($r = -0.39$, $p = 0.026$) in a study conducted in the Kumasi Metropolis. Similarly, [60] found significant negative correlations between CO and relative humidity during the pre-monsoon season ($r= -0.4732$, $p<0.05$) but observed positive correlations during the monsoon ($r=0.1442$) and winter ($r=0.1914$) seasons. Additionally, CO was weakly correlated with temperature during the pre-monsoon season ($r=-0.0795$), though this was not statistically significant at $p<0.05$. These findings suggest that CO can exhibit significant correlations with meteorological parameters, including relative humidity, under specific conditions.

In a study, also documented negative correlations between NO_x and $PM_{2.5}/PM_{10}$ in the pre-monsoon and post-monsoon [60]. Additionally, varying degrees of negative correlations were observed between NO_x and temperature during these seasons. However, no strong positive correlations with temperature were reported. In contrast, a regional study in Bangladesh by [61] noted a positive association between NO_2 and temperature, with an average geographically varying coefficient of 0.12 Dobson Units (DU, where 1 DU = 2.687×10^{16} molecules/cm^2), indicating that NO_2 concentrations increased by 0.12 DU/year for every unit increase in temperature. This aligns with findings in this study which showed a highly significant positive correlation between temperature and NO_x.

Winneba, being a coastal region, experiences high relative humidity, which significantly influences air quality. Elevated relative humidity can increase the size of $PM_{2.5}$ particles, enhance their extinction properties, and reduce visibility [62]. Consistent with our findings, [60] observed significant positive correlations between $PM_{2.5}$ and PM_{10} during post-monsoon and winter seasons. Additionally, $PM_{2.5}$ and PM_{10} in their study [45] showed significant negative correlations with temperature during pre-monsoon, post-monsoon, and winter seasons, aligning with our results.

Our study reports a significant positive correlation between PM_{10} and relative humidity, whereas [60] observed negative correlations between PM_{10} and relative humidity during pre-monsoon, monsoon, and post-monsoon seasons. A positive correlation between temperature and NO_x during the post-monsoon season was also highlighted by [60], supporting our findings of a highly significant positive correlation between these variables. Furthermore, [60] documented a general negative correlation between relative humidity and NO_x across seasons in Bangladesh, which aligns with our study, where relative humidity showed a highly significant negative correlation with NO_x.

Table 6. Correlations of air pollutants with climatological parameters at the study roads

		CO	**NO_X**	**$PM_{2.5}$**	**PM_{10}**	**Temp.**	**RH**
CO	Pearson Correlation	1					
	Sig. (2-tailed)						
NOX	Pearson Correlation	-.089	1				
	Sig. (2-tailed)	.783					.
$PM_{2.5}$	Pearson Correlation	-.051	$-.868^{**}$	1			.
	Sig. (2-tailed)	.874	.000				
PM_{10}	Pearson Correlation	.164	$-.685^{*}$	$.640^{*}$	1		
	Sig. (2-tailed)	.610	.014	.025			
Temp.	Pearson Correlation	-.021	$.882^{**}$	$-.911^{**}$	$-.690^{*}$	1	
	Sig. (2-tailed)	.948	.000	.000	.013		
RH	Pearson Correlation	.121	$-.873^{**}$	$.923^{**}$	$.709^{**}$	$-.979^{**}$	1
	Sig. (2-tailed)	.709	.000	.000	.010	.000	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Regression analysis between air pollutants and weather conditions

Table 7 presents the results of a regression analysis examining the relationship between air pollutants (CO, NO_x, $PM_{2.5}$, PM_{10}) and two independent variables: Relative Humidity (RH) and temperature (Temp.). The R-squared values were consistent across both independent variables, indicating that the models explained similar proportions of variance. However, none of the models achieved statistical significance, as all p-values exceeded 0.05, suggesting that neither RH nor Temperature significantly predicted pollutant levels.

For CO, the R^2 value was 0.238, indicating that only 23.8% of the variance in CO levels was explained by RH and Temp., with t-values ranging from 1.6 to 1.7 and p-values exceeding 0.1. Similarly, NO_x exhibited an R^2 of 0.78 but showed no significant relationship with either independent variable. While $PM_{2.5}$ and PM_{10} had higher R^2 values of 0.853 and 0.504 respectively, their high p-values indicated a lack of significant predictive power. Overall, the analysis does not support the hypothesis that temperature or relative humidity significantly influences air pollutant levels in the study area.

These findings align with assertions from several scholars who have observed varying relationships between urban air pollution characteristics and meteorological conditions. Some studies reported positive correlations between pollutant concentrations and relative humidity [63-65], while others documented negative correlations in different cities [66-68]. Notably, highlights that fluctuations in air pollution and meteorological variations can significantly exacerbate skin conditions in patients with Atopic Dermatitis (AD), worsening their symptoms and skin responsiveness [69].

Table 7. Regression analysis between air pollutants and weather conditions in the municipality

Dependent Variable	**Independent Variable**	**R^2**	**F**	**t-value**	**B**	**SEB**	**p-value**	**Hypothesis Support**
CO	RH	0.238	1.405	1.675	169.716	101.327	0.128	No
	Temp.			1.625	728.592	448.495	0.139	No
NO_X	RH	0.78	15.931	-0.328	-1.512	4.608	0.75	No
	Temp.			0.833	16.988	20.398	0.426	No
$PM_{2.5}$	RH	0.853	26.099	1.198	5.586	4.661	0.261	No
	Temp.			-0.286	-5.903	20.632	0.781	No
PM_{10}	RH	0.504	4.565	0.708	4.44	6.273	0.497	No
	Temp.			0.091	2.534	27.764	0.929	No

Conclusion

This study revealed critical air pollution from vehicular emissions along major highways in Winneba, Ghana. The measured concentrations of NO_x, CO, $PM_{2.5}$, and PM_{10} consistently exceeded the limits set by WHO and USEPA, with exceedance factors categorizing the area as "critically polluted." Despite no statistically significant variations across the sampling roads, the levels of these pollutants reflected a widespread vehicular pollution issue. The Air Quality Index (AQI) further classified all monitored roads as "extremely polluted," underscoring the severity of the problem. Elevated pollutant levels present potential public health risks, including respiratory and cardiovascular diseases which are linked with air pollution.

Future studies should encompass a broader range of pollutants, including ozone and heavy metals, while evaluating seasonal and meteorological factors influencing pollutant dynamics. Additionally, research should prioritize the use of bioindicators as cost-effective tools for monitoring vehicular pollution, offering a sustainable alternative for air quality assessment.

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Competing interests

The authors declare no conflicts of interest.

Authors' contributions

Conceptualization: Francis Kwaku Nkansah and Ebenezer J. D. Belford; Methodology: Francis Kwaku Nkansah, Ebenezer J. D. Belford, Jonathan Nartey Hogarh, and Alfred Kwablah Anim; Formal analysis: Francis Kwaku Nkansah; Investigation: Francis Kwaku Nkansah; Resources: Jonathan Nartey Hogarh; Data curation: Alfred Kwablah Anim; Writing—original draft preparation: Francis Kwaku Nkansah; Writing—review and editing: Ebenezer J. D. Belford, Jonathan Nartey Hogarh, and Alfred Kwablah Anim; Supervision: Ebenezer J. D. Belford, Jonathan Nartey Hogarh, and Alfred Kwablah Anim. All authors have read and approved the published version of the manuscript.

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Ethical considerations

This study did not involve humans or animals as subjects, there was no harm anticipated to human or animal life. Ethical issues (Including plagiarism, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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