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Comprehensive health risk assessment of urban ambient air pollution ($PM_{2.5}$, NO_2 and O_3) in Ghana

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ABSTRACT

Urbanization and industrialization have drastically increased ambient air pollution in urban areas globally from vehicle emissions, solid fuel combustion and industrial activities leading to some of the worst air quality conditions. Air pollution in Ghana causes approximately 28,000 premature deaths and disabilities annually, ranking as a leading cause of mortality and disability-adjusted life years. This study evaluated the annual concentrations of $PM_{2.5,}$ NO_2 and O_3 in the ambient air of 57 cities in Ghana for two decades using historical and forecasted data from satellite measurements. The study assessed urban air quality and evaluated both carcinogenic and non-carcinogenic health risks associated with human exposure to ambient air pollutants. Alarmingly, our findings revealed the yearly median $PM_{2.5}$ concentrations (50.79–67.97 $\mu g\ m^{-3}$) to be significantly higher than the WHO recommendation of 5 $\mu g\ m^{-3}$. Tropospheric ozone concentrations (72.21–92.58 $\mu g\ m^{-3}$) also exceeded the WHO annual standard of 60 $\mu g\ m^{-3}$. Furthermore, NO_2 concentrations (3.65–12.15 $\mu g\ m^{-3}$) surpassed the WHO threshold of 10 $\mu g/m^3$ in multiple cities. Hazard indices indicated that $PM_{2.5}$ and O_3 pose significant non-carcinogenic health risks for younger age groups for a daily exposure duration of three hours and beyond. According to the Air Quality Life Index (AQLI) in our study, exposure to $PM_{2.5}$ shortens life expectancy by 4.5–6.2 years. The ambient air of the majority (98 %) of the cities was unhealthy for sensitive groups. This study reveals the urgent need for comprehensive air quality policies in Ghanaian cities. It emphasizes the significance of robust real-time monitoring of air pollutants and the investigation of seasonal dust storm effects, to fill data gaps in Ghana and West Africa, facilitating evidence-based interventions that improve urban air quality and public health outcomes.

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1. Introduction

Air is a mixture of gases and tiny dust particles. It is a basic element of life, as a source of oxygen needed for respiration. It is a microbial habitat and a superhighway for the water cycle (Ababio, 2023). Air pollution is caused by human activities or natural processes that introduce harmful substances into the air, posing risks to the health and well-being of humans and endangering the ecosystem at large. Ambient air pollution is a major health risk in the 21st century. It is responsible for millions of annual premature mortalities across the globe in urban and rural environments (Li et al., 2023). Half of the world's population resides in urban cities where they are exposed to gaseous and particulate pollutants (Fan et al., 2020). It is projected that by 2050 approximately 70 % of the global population will live in urban areas (Sicard et al., 2023). Nitrogen dioxide (NO_2), particulates with aerodynamic sizes of 2.5 µm ($PM_{2.5}$) and tropospheric ozone (O_3) are among the most harmful air pollutants to public health in urban settings (Sicard et al., 2020; Cakaj et al., 2023). Millions of people are exposed to the concentrations of these pollutants at levels beyond the WHO-recommended thresholds (Anenberg et al., 2022; Sicard et al., 2021; Southerland et al., 2022). Chronic exposure to these pollutants results in increased risks of ischaemic heart disease, stroke, acute lower respiratory infections, chronic obstructive pulmonary diseases, acute kidney injury, dementia, cognitive decline, liver and lung cancer (Kumar et al., 2023; Wang et al., 2023; Ma et al., 2023; 2024).

Urbanization and industrialization have led to a significant increase in ambient air pollution levels in urban cities across the globe making them have some of the worst air quality on the planet. Anthropogenic sources of air pollution comprise vehicle emissions, the combustion of solid fuels and domestic waste as well as industrial, agricultural, construction and mining activities (Nyarku et al., 2021; Okedere et al., 2021). The Global Burden of Disease estimates ambient air pollution to be a primary contributor to global mortality and the loss of disability-adjusted life years, with 4 million premature deaths annually linked to it (Johnson et al., 2024). Air pollution is the second-highest risk factor in Ghana, accounting for about 28,000 premature deaths and disabilities per annum (Ababio et al., 2023). The World Bank estimates that the annual cost of air pollution in Ghana is 4.2 % of GDP, which is equivalent to US $2.5 billion. Also, it costs approximately US $264 million per annum alone for the largest urban cities, in Ghana, such as Accra and Kumasi (World Bank Group, 2020).

Various kinds of studies including monitoring and measurement studies, epidemiological investigations, source apportionment analyses, air quality modeling, policy and regulatory assessments, control and mitigation studies have been conducted on air pollution in the ambient environment across the globe. Despite these numerous studies, the state of ambient air pollution in urban cities in Sub-Saharan Africa specifically Ghanaian cities remains understudied. This is due to factors such as the lack of air quality monitoring instruments, unenforced national emissions standards, limited funding for research initiatives, insufficient infrastructure for data collection and analysis, and disparities in the prioritization of environmental health.

Notable among recent studies on ambient air pollution in Ghana include a survey on the knowledge, perception and awareness of air pollution by Odonkor and Mahami (2020). The study reported that most of its respondents who were residents of the capital city, Accra, knew about air pollution and its recurring impacts on their health. An air quality study of 130 locations in the Greater Accra Metropolis by Wang et al. (2024) predicted annual, harmattan and non-harmattan mean NO_2 levels for the metropolis to be 37, 50, and 28 $\mu g\ m^{-3}$ respectively. The study identified road traffic as the primary source of NO_2 emissions with the annual levels in the city exceeding the World Health Organization (WHO) guideline of 10 $\mu g\ m^{-3}$. A $PM_{2.5}$ monitoring study by Amegah et al. (2022) in ten different traffic hotspots in Accra during the dry and wet seasons reported median levels ranging from 27.08 – 51.37 and 20.04 – 48.92 $\mu g\ m^{-3}$ respectively. An increase of 1 $\mu g\ m^{-3}$ in $PM_{2.5}$ exposure was associated with slight increases in respiratory and cardiovascular, and symptoms among street traders. Nyadanu et al. (2022) recorded an annual $PM_{2.5}$ average of 59.97 $\mu g\ m^{-3}$ with an increase of 10 $\mu g\ m^{-3}$ in the annual average linked with a 3 % risk of stillbirth.

Existing studies on ambient air pollution in Ghana have focused on the capital city, Accra, making the air quality status of other cities unknown (Arku et al., 2008, 2015; Armah et al., 2010; Ofosu et al., 2012; Rooney et al., 2012; Dionisio et al., 2010; Odonkor and Mahami 2020; Kanhai et al., 2021; Amegah et al., 2022; Alli et al., 2023; Wang et al., 2024). Expanding the evaluation of ambient air pollution beyond Accra is crucial for a comprehensive assessment of air quality across Ghana. Without up-to-date information on the trend of ambient air pollutants for different urban cities in Ghana over the past two decades, policymakers will face challenges in identifying priority areas for intervention and evaluating the efficacy of existing measures.

This study conducts a comprehensive health risk assessment of ambient air pollutants in urban cities across Ghana from the year 2000–2023. It evaluates urban air quality and health risks of long-term exposure to $PM_{2.5}$, O_3 and NO_2 in the urban population of Ghana. Furthermore, this study is crucial for addressing health inequalities as it sheds light on how vulnerable populations such as the elderly and children are affected by urban air quality. It provides essential information to aid the tailoring of nation-specific public health interventions. To the best of our knowledge, this study is the first to comprehensively assess the ambient air quality of urban cities across different regions of Ghana. This study seeks to inform policymakers, the scientific community and public health officials about the status of urban air pollution in Ghana. This study not only fills a critical gap on urban air quality in Ghana but serves as a benchmark for facilitating informed decision-making processes, equipping stakeholders with the knowledge needed to develop effective evidence-based strategies to improve air quality and safeguard the public health of urban populations in the country

2. Methodology

2.1. Study area

Ghana is situated in Sub-Saharan Africa, along the West African coast, bordered by Côte d'Ivoire to the west, Burkina Faso to the north, Togo to the east, and the Gulf of Guinea to the south. Its diverse landscape includes coastal plains, tropical rainforests, savannahs, and the Volta River Basin. It covers a land area of approximately 240,000 km^2 with a population of about 30 million people (Agodzo et al., 2023). A majority of this population (57 %) reside in urban areas with almost half of this urban population living in the Accra and Kumasi Metropolis (Ghana Statistical Service, 2021; Iddrisu et al., 2023). The urban cities involved in this study are illustrated in Fig. 1.

2.2. Data

This study used air quality observation data for 57 urban cities in different regions of Ghana from 2000 to 2019. The data were obtained from https://urbanairquality.online/ which provides a downloadable dataset of air pollutant concentrations in all cities worldwide, as described below. The obtained historical data from 2000 to 2019 for the 57 urban cities were used to estimate forecast values for 2020–2023 by employing time series forecasting in Excel with a 95 % confidence interval using the Exponential Smoothing (ETS) method. The retrieved data included annual concentrations and population attributable fraction (%) (PAF) for $PM_{2.5}$, O_3 and NO_2 in 57 Ghanaian urban cities.

The obtained $PM_{2.5}$ urban data were from a higher spatial resolution dataset (1 km x 1 km) which integrated information from satellite-retrieved aerosol optical depth, chemical transport modeling, and ground monitor data incorporating geographically weighted regression. Southerland et al. (2022) provide additional details on the method used to generate the $PM_{2.5}$ dataset. The obtained O_3 data were from combined

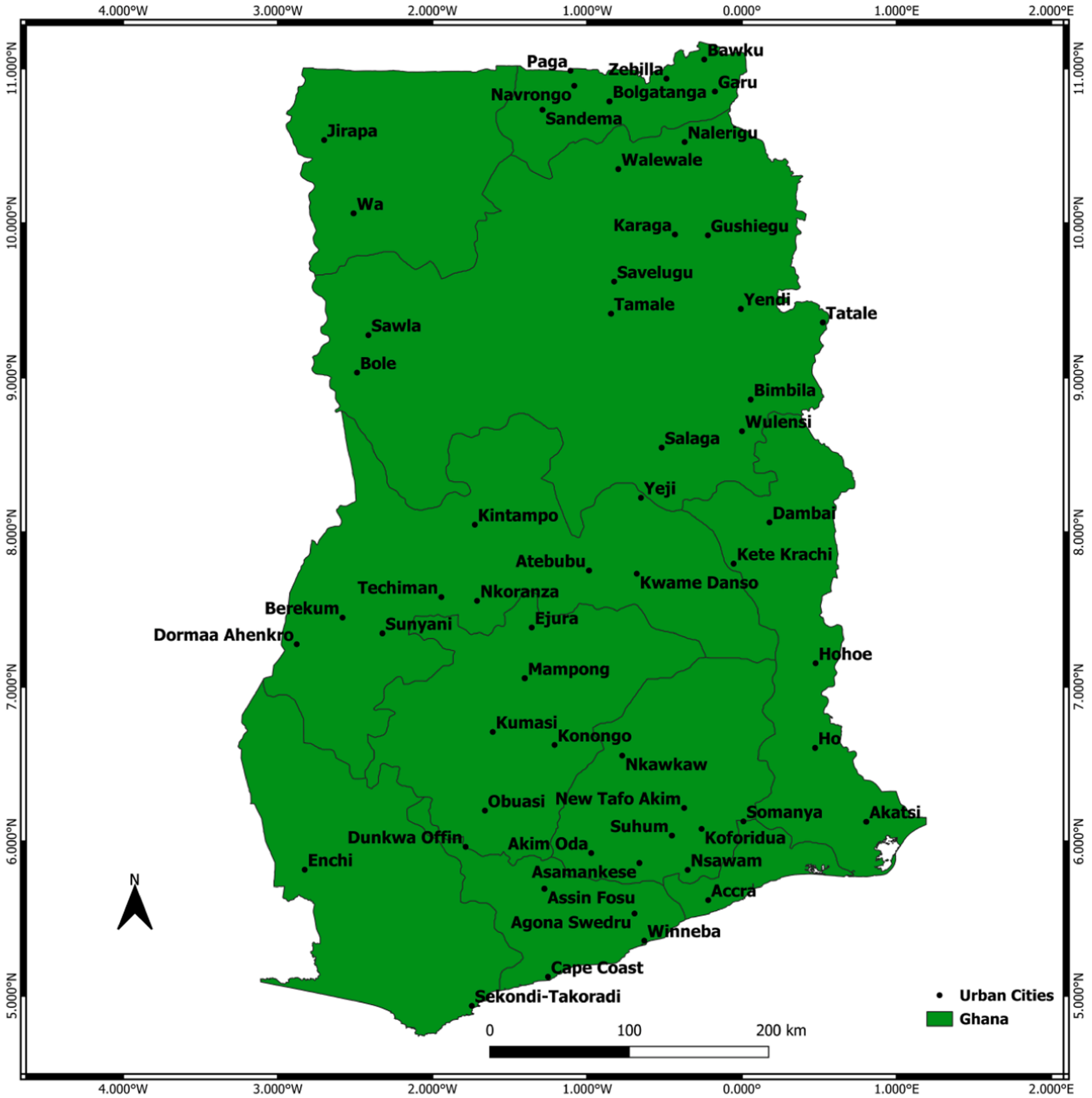

Fig. 1. Map of Ghana showing the 57 urban cities in the study.

ground measurement data with chemical transport model estimates, downscaled to create finer resolution ozone concentration estimates from 1990 to 2017 which were further extrapolated to 2019 based on log-linear trends from 2008 to 2017 and re-gridded to a spatial resolution of 1 km to align with population estimates. Further information regarding the method utilized to generate the O_3 dataset can be found in Malashock et al. (2022). The obtained NO_2 data were from a resolution of approximately 1 km^2, calculated in 5-year increments between 1990 and 2010, and annually from 2010 to 2019. Additional details about the methodology used in generating the NO_2 dataset are provided by Anenberg et al., (2022).

The concentrations in parts per billion (ppb) were converted to μg/m^3 using 1 ppb $NO_2 = 1.88$ μg/m^3 and 1 ppb $O_3 = 1.96$ μg/m^3 (Shen et al., 2023). In addition, the population attributable fraction (%) (PAF) for $PM_{2.5}$, O_3 and NO_2 per annum also obtained from https://urbanairquality.online were used to estimate the mortality, disability-adjusted life years (DALY), years of healthy life lost due to disability (YLD), years of life lost from mortality (YLL) associated with ambient urban air pollution in Ghana. These estimates were made for Chronic Respiratory Diseases (CRD) and also specifically for Chronic obstructive pulmonary disease (COPD), pneumoconiosis, asthma and Interstitial Lung disease and pulmonary sarcoidosis (ILDS). The national burden of chronic respiratory diseases used for the estimates was retrieved from the Global Burden of Disease Study in 2019 (Momtazmanesh et al., 2023).

2.3. Ambient air quality

Ambient air quality is the extent to which the ambient air is free of pollution and healthy for breathing. This can be assessed using a standard numerical rating known as the air quality index (AQI) (Table S1) (Ababio et al., 2024). AQI is estimated from the concentrations of air pollutants that are considered criteria for air quality. The sub-air quality ratings of the ambient air pollutants ($PM_{2.5}$, O_3 and NO_2) were used to compute the air quality index. The worst sub-air quality indices were used to adjudge the overall air quality index for each city and year in this study. The sub-air quality indices for each air pollutant were calculated using Eq. (1) (Abdul Raheem et al., 2022).

$$I_P = (C_P - BP_{Lo}) x \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} + I_{Lo} \tag{1}$$

where I_P: Index value for the air pollutant

C_P: Concentration of air pollutant

BP_{Lo}: Lower Breakpoint value of C_P

BP_{Hi}: Higher Breakpoint value of C_P

I_{Hi}: Index Breakpoint value of BP_{Hi}

I_{Lo}: Index Breakpoint value of BP_{Lo}

The breakpoint values for the concentrations of the air pollutants are provided in Table S2. The six classifications of air quality index have with their respective colour codes and ranges which are provided in Table S1.

2.4. Dominant pollution types of $PM_{2.5}$ and O_3

The respective annual concentration thresholds [$PM_{2.5} = 5$ µg m^{-3}, $O_3 = 60$ µg m^{-3}] were used to categorize the dominant pollution types of $PM_{2.5}$ and O_3 into four which are; Compound Pollution of $PM_{2.5}$ and O_3 (P-O), $PM_{2.5}$ Dominant Pollution, O_3 Dominant Pollution, and Clean. The categorization criteria which were modified from He et al. (2024) are given in Table S3.

2.5. Analysis of synergistic changes in compound pollution

The relative rate of change (ROC) of $PM_{2.5}$ and O_3 concentrations in 2000 and 2023 was used to quantify the degree of synergistic changes in pollution levels for the urban cities using Eq. 2 and Eq 3. (He et al., 2024).

$$ROC_i = \frac{C_{i,\ 2023}}{C_{i,\ 2000}} \tag{2}$$

$$\text{If} = \begin{cases} ROC_i, PM_{2.5} \geq 1 \text{ and } ROC_i, O_3 \geq 1 \text{ Synergistic Increase} \\ ROC_i, PM_{2.5} < 1 \text{ and } ROC_i, O_3 < 1 \text{ Synergistic Decrease} \\ ROC_i, PM_{2.5} \geq 1 \text{ and } ROC_i, O_3 < 1 \ PM_{2.5} \text{ Increase and } O_3 \text{ Decrease} \\ ROC_i, PM_{2.5} < 1 \text{ and } ROC_i, O_3 \leq 1 \ PM_{2.5} \text{ Decrease and } O_3 \text{ Increase} \end{cases} \tag{3}$$

2.6. Health risk assessment

2.6.1. Daily dose

Daily Dose (DD) is the chronic inhalation of an ambient air pollutant daily. DD was calculated using Eq. (4) which was modified from (Ababio et al., 2023). The parameter values for different age groups used for evaluating the corresponding health risks for 1 h, 3 h, 6 h, 9 h and 12 h of exposure to the air pollutants have been provided in Table 1.

$$DD = \frac{C \ x \ R \ x \ T \ x \ F \ x \ D}{BWxAT} \tag{4}$$

where C: Concentration of $PM_{2.5}$ or NO_2 or O_3

R: rate of inhalation (m^3 hr^{-1})

T: time of exposure

F: frequency of exposure (365 d yr^{-1})

D: duration of exposure

BW: average body weight

AT: average time (duration of exposure x frequency of exposure)

The parameter values used for estimating the daily dose in the study were adopted from the exposure factor handbook of the United States Environmental Protection Agency (2011). The employed values are provided in Table 1.

2.6.2. Non-carcinogenic risk

As a ratio between the daily dose and reference dose, the Hazard Quotient (HQ) reveals how the ambient air pollutant compares to its reference dose. The hazard quotient and Hazard index (HI) are indicators of non-carcinogenic health risks calculated using Eq. 5 and Eq. 6 (Ababio et al., 2023). HI predicts the sum of the individual HQ for the criteria pollutants through an exposure route to the reference dose (RfD) for each pollutant (Hogarh et al., 2018). An HI/HQ < 1 and HI/HQ > 1 imply negligible non-cancer health risk and a higher chronic non-cancer risk respectively.

$$HQ = \frac{DD}{RfD} \tag{5}$$

$$HI = HQPM_{2.5} + HQNO_2 + HQO_3 \tag{6}$$

The reference dose (RfD) determined using Eq. (7) is the concentration at which daily exposure to a pollutant such as $PM_{2.5}$, O_3, and NO_2 does not cause adverse health effects over a lifetime (Ababio et al., 2023).

$$RfD = \frac{RfC \ x \ IR}{BW} \tag{7}$$

Where RfC: Reference concentration (WHO annual guideline values $PM_{2.5} = 5$ µg m^{-3}, $O_3 = 60$ µg m^{-3} and $NO_2 = 10$ µg m^{-3} (World Health Organization, 2021)

IR: Inhalation rate (m^3 d^{-1})

BW: average body weight

2.6.3. Carcinogenic risk for $PM_{2.5}$ exposure

The carcinogenic risk which is the incremental chance of developing cancer from exposure to ambient $PM_{2.5}$ in urban cities was calculated using Eq. (8). The accepted range for carcinogenic risk is 10^{-4} to 10^{-6}, as risks $< 10^{-6}$ are considered negligible and $> 10^{-4}$ are considered highly unacceptable and a cause for alarm.

$$CR = DD \ x \ SF \tag{8}$$

The slope factor (SF) was used to estimate the likelihood of developing cancer from exposure to a carcinogenic pollutant such as ambient $PM_{2.5}$. SF was calculated using Eq. (9) for adults, adolescents, children, toddlers and infants (Mbazima, 2022).

$$SF = \frac{IUR}{BWxIR} \tag{9}$$

Where SF: Slope Factor

IUR: Inhalation Unit Risk (0.008)

IR: Inhalation rate

BW: average body weight

Table 1

Parameter values for estimating the daily dose in different age groups.

Age Group	Inhalation rate (m^3 d^{-1})	Exposure duration (yrs)	Body weight (kg)
Infant	5	1	7
Toddler	9	4	12
Children	12	12	23
Adolescents	16	19	62
Adults	20	70	70

2.6.4. Relative and excess risk

2.6.4.1. Relative risk. Relative risk (RR) is a measure of the degree of correlation between exposure to a particular pollutant and the likelihood of developing health outcomes such as a disease or mortality. RR was obtained using Eq. (10) (Sharma et al., 2023).

$$RR = \exp\left[\beta\left(C - C_o\right)\right] \tag{10}$$

Where β: the exposure-response coefficient is the corresponding additional health risk per unit increase in an air pollutant beyond its threshold concentration. $\beta = 0.038\ \%$, 0.13 % and 0.048 % per 1 $\mu g\ m^{-3}$ increase of $PM_{2.5}$, NO_2 and O_3 respectively. (Shen et al., 2020)

C: Concentration of $PM_{2.5}$ or NO_2 or O_3

C_o: the threshold concentration (WHO annual guideline values)

2.6.4.2. Excess risk. Excess Risk (ER) is the difference in risk between exposed and unexposed individuals. It was used to estimate the additional risk of health outcomes or mortalities due to exposure to the pollutant. ER was computed using Eq. (11) (Sharma et al., 2023)

$$ER = RR - 1 \tag{11}$$

Where RR: Relative Risk

2.6.5. Air quality life index

The Air Quality Life Index (AQLI) estimates the impact of air pollution on life expectancy (Greenstone and Fan, 2018). It measures the potential gains in life expectancy per person (Life Years Saved) if $PM_{2.5}$ concentrations meet WHO or national air quality standards. It is based on findings that sustained exposure to an additional 10 $\mu g\ m^{-3}$ of $PM_{2.5}$ above the recommended threshold reduces life expectancy by 0.98 years (Chen et al., 2013; Ebenstein et al., 2017; Greenstone and Fan, 2018; Rana, 2022). It was calculated using Eq. (12)

$$\text{Life Years Saved} = \left(\frac{C - S}{10}\right) x\ 0.98 \tag{12}$$

Where C = the annual concentration of $PM_{2.5}$ in $\mu g\ m^{-3}$

S = $PM_{2.5}$ WHO annual guideline value = 5 $\mu g\ m^{-3}$

2.6.6. Mortality, Disability-Adjusted Life Years (DALY), Years of Healthy Life Lost due to Disability (YLD) and Years of Life Lost from Mortality (YLL) estimates for all age groups

The estimates for the deaths, DALY, YLD and YLL associated with ambient concentrations of $PM_{2.5}$, NO_2 and O_3 were made to assess the impact on respiratory health burden in Ghana. Using the annual median population attributable fraction (%) (PAF) data spanning from 2000 to 2023, the adjusted deaths, DALYs, YLLs, and YLDs for CRD and specific respiratory diseases (COPD, pneumoconiosis, asthma, and ILSD) were calculated accordingly using Eqs. (13), (14), (15), (16), (17) and (18). The mortality, DALY, YLL and YLD values for Ghana from the Global Burden of Disease Study in 2019 (Momtazmanesh et al., 2023) used for the estimation are provided in Table S4.

$$Incidence_{PM_{2.5}\ or\ NO_2\ or\ O_3} = \text{Mortality}_{\text{disease}}\ x\ PAF_{PM_{2.5}\ or\ NO_2\ or\ O_3} \tag{13}$$

$$Prevalence_{PM_{2.5}\ or\ NO_2\ or\ O_3} = \text{Mortality}_{\text{disease}}\ x\ PAF_{PM_{2.5}\ or\ NO_2\ or\ O_3} \tag{14}$$

$$Mortality_{PM_{2.5}\ or\ NO_2\ or\ O_3} = \text{Mortality}_{\text{disease}}\ x\ PAF_{PM_{2.5}\ or\ NO_2\ or\ O_3} \tag{15}$$

$$DALY_{PM_{2.5}\ or\ NO_2\ or\ O_3} = \text{Mortality}_{\text{disease}}\ x\ PAF_{PM_{2.5}\ or\ NO_2\ or\ O_3} \tag{16}$$

$$YLL_{PM_{2.5}\ or\ NO_2\ or\ O_3} = \text{Mortality}_{\text{disease}}\ x\ PAF_{PM_{2.5}\ or\ NO_2\ or\ O_3} \tag{17}$$

$$YLD_{PM_{2.5}\ or\ NO_2\ or\ O_3} = \text{Mortality}_{\text{disease}}\ x\ PAF_{PM_{2.5}\ or\ NO_2\ or\ O_3} \tag{18}$$

2.7. Statistical analysis

The retrieved data underwent statistical analysis using the Stata and Microsoft Excel. Quantile regression was employed in this study to analyze the relationship between ambient air pollution in urban cities.

It was used in this study due to the skewed distribution exhibited by the obtained data. It was used to estimate the median and other quantiles of ambient air pollutant concentrations. It allowed for the comparison of the quantile estimates across urban cities. It made it possible to assess the differences in pollutant concentrations for the different years. Additionally, regression coefficients (β) were also estimated from quantile regressions.

The p-values associated with the regression coefficients were also generated using quantile regression which indicated the statistical significance of the differences in pollutant levels between the cities. Moreover, the Kendall Tau (KT) test was also used to assess trends in the time series data of the air pollutants.

The Kendall's tau coefficients (τ_a and τ_β) and the associated p-value were estimated. Kendall's tau coefficients were used to measure the association between the variables "year" and "pollutant concentration", with positive values indicating an increasing trend, negative values indicating a decreasing trend, and values close to zero indicating no significant trend. The associated p-value provided a measure of the statistical significance of the observed trend. In addition, Sen's slope was also employed to analyze trends in pollutant concentrations over time using the estimated slope coefficient, p-value which determined the significance level, and the confidence interval which assessed the precision and reliability of the estimated trend. Moreover, Principal Component Analysis (PCA) was used to analyze air pollutant patterns in the various urban cities compressing the dataset into components to reveal the relationship between pollutants and their spatial distribution.

3. Results and discussion

3.1. Ambient air pollutant concentrations, population attributable fraction (%), epidemiological impacts and air quality indices of the urban cities

The annual concentrations of $PM_{2.5,}$ $NO_{2,}$ and O_3 for different urban cities in Ghana from 2000 to 2023 are reported as median and quartiles in Table 2. The corresponding p-values, regression coefficients, and confidence intervals for the annual concentrations of $PM_{2.5,}$ $NO_{2,}$ and O_3 using the capital city, Accra as the reference are provided in Tables S1 and S2. The annual $PM_{2.5,}$ and O_3 concentrations for each city in the study are provided in Fig. S1a – Fig. S1e and that of NO_2 in Fig. S2a – Fig. S2e.

The annual median $PM_{2.5}$ concentrations of the urban cities spanned from 50.79 to 67.97 $\mu g\ m^{-3}$. These were five to six-fold higher than the WHO annual $PM_{2.5}$ air quality guideline value (5 $\mu g\ m^{-3}$). Spatial distribution revealed the urban populace in Akatsi and Jirapa situated in Southeastern and Northwestern Ghana to be exposed to the highest and lowest median annual $PM_{2.5}$ concentrations respectively (Fig. 2a).

It was observed that cities such as Accra, Koforidua, and Kumasi in the Southern regions of Ghana consistently exhibited higher annual median $PM_{2.5}$ concentrations compared to lower levels in cities in the Northern belt such as Wa, Tamale, and Nalerigu. The $PM_{2.5}$ findings of this study were similar to the findings of Moro et al. (2022) as Savannah belt cities had the lowest $PM_{2.5}$ concentrations, followed by Forest belt and Coastal belt cities. The inter-urban comparison of $PM_{2.5}$ concentrations using the capital city, Accra, as the reference indicated 20 of the urban cities in the study to have positive regression coefficients (β) (0.31 – 7.80) (Table S5). These revealed residents of these cities to be exposed to higher levels of $PM_{2.5}$ as compared to urban dwellers in the capital. These might be attributed to anthropogenic factors such as higher reliance on traditional biomass cooking sources, lack of green spaces, untarred roads, and combustion of waste coupled with meteorological

Table 2
Concentrations of $PM_{2.5}$, NO_2 and O_3 in Ghanaian Urban Cities.

City	$PM_{2.5}$ ($\mu g\ m^{-3}$)		O_3 ($\mu g\ m^{-3}$)		NO_2 ($\mu g\ m^{-3}$)	
	Median	IQR	Median	IQR	Median	IQR
Accra	61.43	13.53	72.21	24.09	11.06	0.95
Agona Swedru	62.98	15.93	73.04	24.41	6.25	0.48
Akatsi	67.97	11.98	78.48	24.99	6.96	0.53
Akim Oda	62.33	19.08	80.09	24.34	6.65	0.34
Asamankese	63.42	16.18	80.59	24.33	4.94	0.35
Assin Fosu	64.80	20.33	74.81	23.30	6.14	0.67
Atebubu	61.93	11.77	89.37	22.98	5.97	1.18
Bawku	58.22	12.47	85.94	16.93	11.43	0.92
Berekum	55.72	13.67	83.99	22.94	7.87	0.76
Bimbila	61.17	9.11	92.01	19.06	8.41	0.93
Bole	56.17	8.90	88.79	15.13	7.91	2.79
Bolgatanga	56.34	9.31	86.43	17.19	11.08	0.95
Cape Coast	60.27	16.95	nd	Nd	3.65	0.28
Dambai	64.56	10.96	90.15	21.42	7.34	1.26
Dormaa Ahenkro	57.64	17.35	80.81	22.96	6.82	0.95
Dunkwa Offin	60.55	17.83	78.23	22.45	5.50	0.57
Ejura	60.29	11.11	87.62	23.87	7.27	0.87
Enchi	59.43	16.26	72.99	21.65	4.69	0.48
Garu	58.07	13.52	87.47	17.55	12.15	0.84
Gushiegu	56.28	8.86	90.88	18.06	10.01	0.70
Ho	63.58	8.00	83.50	26.12	5.88	2.02
Hohoe	64.24	11.20	87.52	24.84	5.31	0.50
Jirapa	50.79	6.87	85.42	16.42	9.08	1.42
Karaga	54.49	10.73	90.59	18.06	9.76	1.84
Kete Krachi	61.91	10.80	90.08	23.62	6.54	1.02
Kintampo	58.24	12.90	88.10	19.60	5.94	1.05
Koforidua	61.14	13.31	81.10	26.05	7.05	0.83
Konongo	59.93	15.82	82.33	24.56	7.00	1.08
Kumasi	63.15	18.65	83.42	24.24	10.27	0.32
Kwame Danso	62.22	12.73	88.77	23.09	6.16	2.61
Mampong	58.81	11.31	85.81	23.88	6.27	0.61
Nalerigu	54.80	7.66	87.49	17.55	11.58	0.40
Navrongo	56.48	9.86	85.65	16.83	9.82	0.67
New Tafo Akim	60.03	13.66	82.55	26.03	6.46	0.45
Nkawkaw	60.43	12.79	83.48	25.47	6.49	0.71
Nkoranza	57.76	12.81	86.33	21.96	5.84	0.86
Nsawam	62.34	15.32	82.35	24.12	8.05	0.47
Obuasi	61.43	18.83	77.51	23.89	7.48	0.56
Paga	55.52	9.27	85.09	16.72	8.86	0.71
Salaga	62.03	9.01	89.40	19.41	7.15	1.78
Sandema	55.83	11.15	85.89	16.83	8.89	1.83
Savelugu	55.60	9.74	90.33	17.81	9.08	1.51
Sawla	55.93	9.48	89.16	15.32	7.52	2.64
Somanya	60.51	11.03	81.45	25.73	6.07	0.60
Suhum	62.09	16.81	80.42	26.06	5.61	0.52
Sunyani	57.26	13.10	83.95	23.36	9.11	1.47
Sekondi-Takoradi	59.27	15.04	nd	Nd	4.66	0.25
Tamale	57.21	11.88	91.43	18.28	10.45	1.42
Tatale	57.71	9.92	92.58	17.45	8.21	1.51
Techiman	57.18	12.55	86.31	21.96	7.35	0.42
Wa	51.57	8.70	86.78	15.87	10.62	2.19
Walewale	55.34	9.80	88.27	17.58	10.17	1.14
Winneba	63.73	16.18	73.58	22.28	5.83	0.41
Wulensi	63.58	10.28	91.23	19.21	7.97	1.67
Yeji	61.65	9.41	89.86	21.19	7.29	1.82
Yendi	55.77	11.38	92.21	18.00	9.72	1.46
Zebilla	56.50	10.92	86.51	17.50	9.80	0.68

IQR means Interquartile range; nd means no data

conditions such as higher temperatures and low wind speeds that could have exacerbated $PM_{2.5}$ pollution in these cities. Negative regression coefficients (β) (-0.40 to −10.40) revealed the majority (36) of residents in the urban cities in this study to be exposed to lower levels of $PM_{2.5}$ as compared to the capital. These might have been due to lower population densities, limited industrial activities and vehicular traffic. Furthermore, fine particulate matter ($PM_{2.5}$) concentrations in the urban cities except Jirapa and Wa were not significantly different from the capital with $p > 0.05$ (Table S5).

The AQLI estimates for gains in life expectancy if ambient $PM_{2.5}$ concentrations per annum in the urban cities met WHO guidelines are given in Fig. 3 and Table S6. The AQLI revealed that ambient $PM_{2.5}$ pollution in urban cities cut life expectancy short by 4.5–6.2 years relative to if concentrations in the cities met the WHO threshold. This revealed the detrimental impact of $PM_{2.5}$ pollution on the life expectancy of habitants in Ghanaian urban cities.

The relative rate of changes for P-O compound pollution and the dominant pollution classifications from the ambient concentrations of $PM_{2.5}$ and O_3 in the urban cities are provided in Table S7. The ambient environment of all the urban cities in the study except Cape Coast and Sekondi Takoradi exhibited a $PM_{2.5}$-O_3 dominant compound pollution as concentrations of $PM_{2.5} > 5\ \mu g\ m^{-3}$ and $O_3 > 31$ ppb. In the absence of corresponding ozone concentrations, the ambient environs of Cape Coast and Sekondi-Takoradi were classified as $PM_{2.5}$ dominated pollution as $PM_{2.5} > 5\ \mu g\ m^{-3}$. The relative rate of changes revealed $PM_{2.5}$-O_3 compound pollution in Sekondi-Takoradi and Cape Coast to have synergistic changes of $PM_{2.5}$ decrease. The observed level of synergistic changes for ambient $PM_{2.5}$-O_3 pollution in Akim Oda and Mampong was synergistic decreases in P-O compound pollution. In contrast, the synergistic increase in P-O compound pollution was observed for Nkawkaw for the study's duration. The remaining 54 urban cities exhibited synergistic changes of $PM_{2.5}$ decrease and O_3 increase for P-O compound pollution from 2000 to 2023. The findings for urban ambient environments in this study was similar to a comparative study by He et al. (2024) which observed P-O compound pollution in majority of global cities, predominantly in urban Asian cities.

The median tropospheric ozone concentrations in the urban cities varied from 72.21 – 92.58 $\mu g\ m^{-3}$ which exceeded the WHO annual guideline equivalent recommendation of 60 $\mu g\ m^{-3}$. The highest and lowest median concentrations of ozone were found in Tatale and the capital, Accra, situated in the Northeastern and Southern parts of the country respectively (Fig. 2b).

Inter-urban comparison indicated cities in Southern Ghana had lower median concentrations of ground-level ozone as compared to higher concentrations in Northern Ghana cities. Furthermore, a comparison of the ozone concentrations in reference to the capital city only gave positive regression coefficients (β) (0.36 – 22.26) (Table S5). This suggested that the urban population of the other cities in the study were exposed to higher concentrations of ground-level ozone than in the capital. This could have been due to factors like cleaner energy initiatives and favourable meteorological conditions for dispersion and degradation that led to the lesser emission of ozone precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) in Accra. Tropospheric ozone concentrations in 33 urban cities were significantly different from that of the capital with $p < 0.05$ while those of 21 cities were not with $p > 0.05$ (Table S5).

Median NO_2 concentrations of the urban cities ranged from 3.65 – 12.15 $\mu g\ m^{-3}$. The highest and lowest were observed in Garu and Cape Coast accordingly. Few of the urban cities had nitrogen dioxide concentrations exceeding the WHO guideline value of 10 $\mu g\ m^{-3}$. Urban cities situated within the Upper East and Northern Regions of Ghana recorded the highest NO_2 concentrations whiles cities in the Central Region of Ghana recorded the lowest (Fig. 2.c).

Positive regression coefficients (β) (0.30 – 0.94) revealed the residents of Bawku, Garu. and Nalerigu to be exposed to concentrations of NO_2 above that of the capital. Furthermore $p > 0.05$ indicated the NO_2 concentrations in Bolgatanga, Bawku, and Wa to be significantly different from that of the capital.

The median $PM_{2.5}$ concentrations per annum varied from 46.69 – 82.52 $\mu g\ m^{-3}$ (Fig. 4A). These were 5 – 8 times above the WHO recommended threshold. The highest was observed in 2000 while the lowest was observed in 2014. The $PM_{2.5}$ concentrations exhibited fluctuations across the 23-year duration. The years 2000 – 2001, 2002 – 2003, 2004 – 2006, 2008 – 2009, and 2012 – 2013 exhibited significant decreases in $PM_{2.5}$ concentrations while significant increases were observed for the years, 2001 – 2002, 2003 – 2004, 2006 – 2007, 2014 – 2015, and 2019 – 2020. In comparison with the year 2000, negative

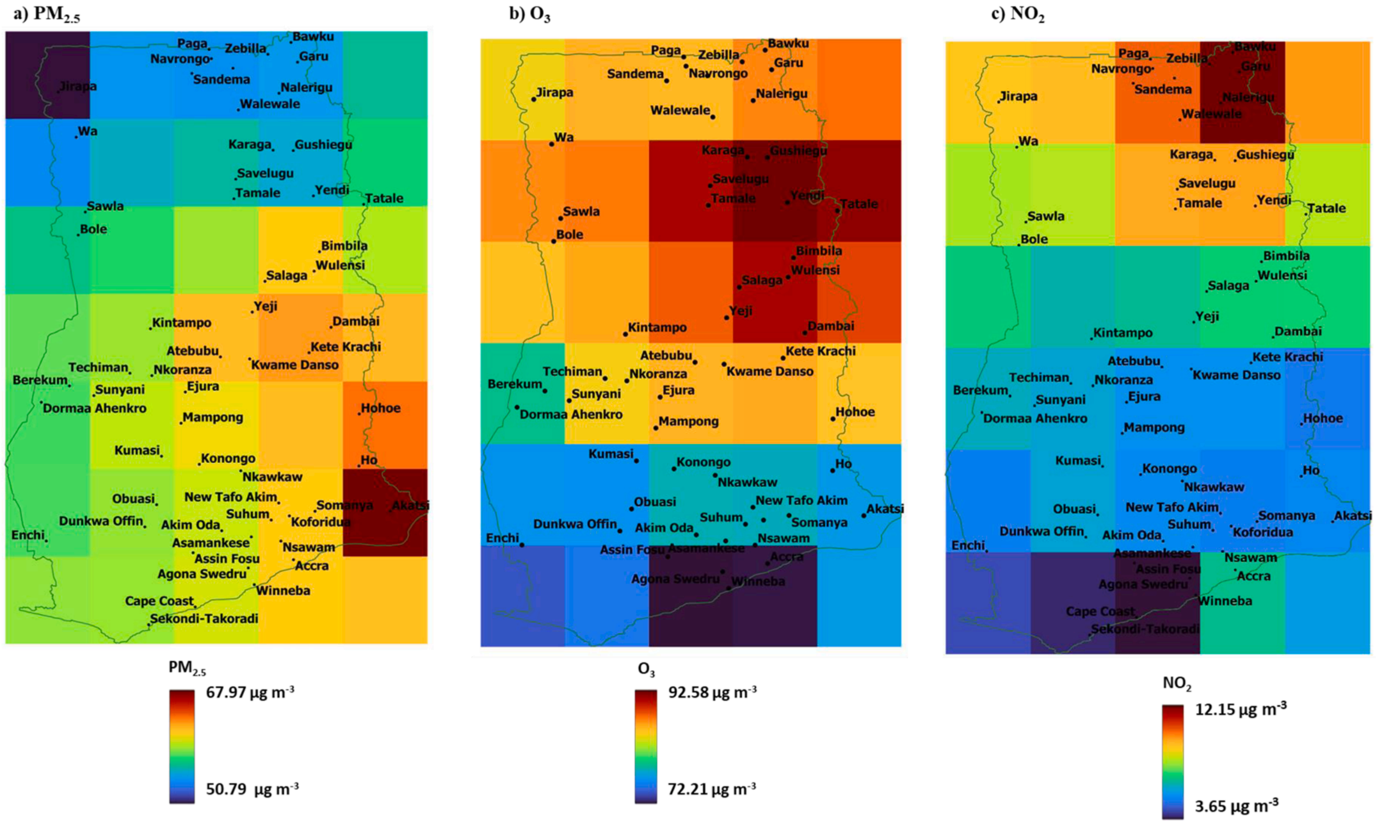

Fig. 2. (a). Spatial Distribution of $PM_{2.5}$ Concentrations in Urban Cities in Ghana (b) Spatial Distribution of O_3 Concentrations in Urban Cities in Ghana (c) Spatial Distribution of NO_2 Concentrations in Urban Cities in Ghana.

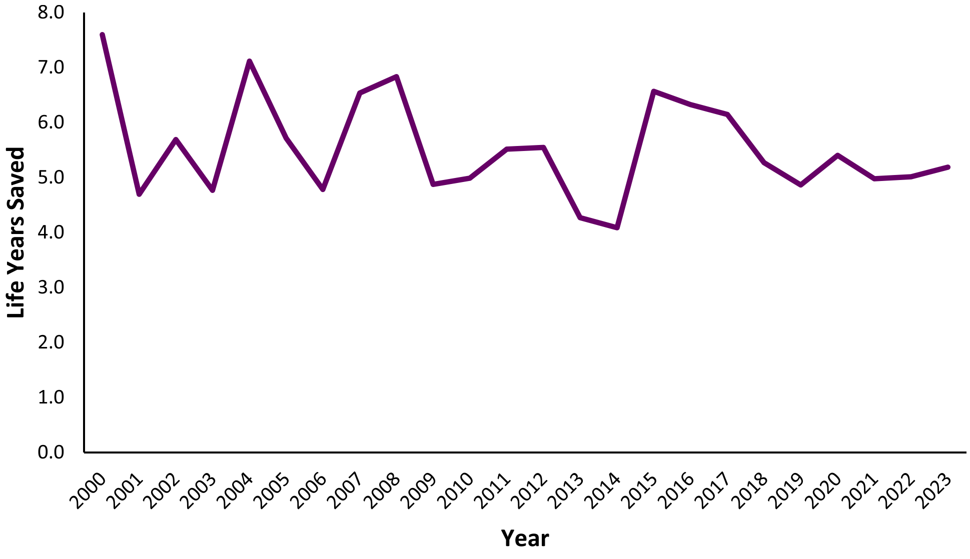

Fig. 3. Life Years Saved per Annum if $PM_{2.5}$ Concentrations met Recommended Threshold.

quantile regression coefficients (β) (-4.90 to −35.83) showed significant reductions in $PM_{2.5}$ concentrations in the urban cities per annum (Table S6). The highest and lowest reductions in annual $PM_{2.5}$ concentrations were observed in the years 2000 and 2014 respectively. The median $PM_{2.5}$ concentrations in the urban cities per annum were significantly different as $p < 0.001$ (Table S8). Negative Kendall tau coefficients (τ) ($\tau_a = -0.1354$ and $\tau_\beta = -0.1383$) and a p-value < 0.0001 were obtained from the KT test which revealed a weak significant negative correlation between years and $PM_{2.5}$ concentrations (Table S9). Also, negative slope coefficient β (-0.14), a p-value < 0.001 and 95 % CI [-0.17, −0.11] were obtained from the Sen's slope analysis (Table S10). These indicated a significant decreasing trend in $PM_{2.5}$ concentrations over the observed years. This could have been due to the transition from biomass combustion sources to cleaner energies such as the increased adoption of liquified petroleum gas for cooking in urban households. Increased greening initiatives such as tree planting programs and the tarring of unpaved roads and streets in urban municipalities reducing the resuspension of dust. Moreover, stringent air quality policies

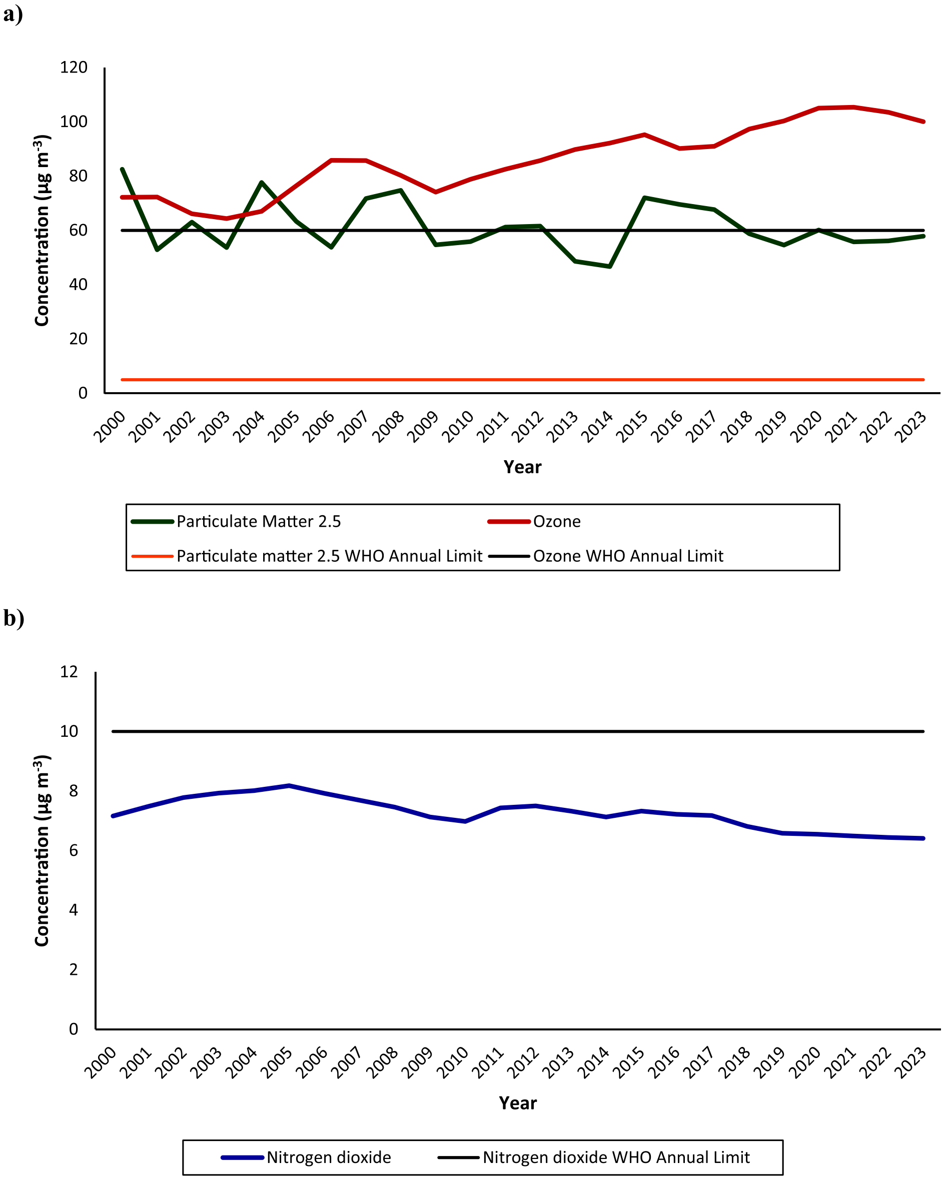

Fig. 4. (a) Annual Median Concentrations of $PM_{2.5}$ and O_3 in Ghanaian Urban Cities (b) Annual Median Concentrations of NO_2 in Ghanaian Urban Cities.

curtailing particulate emissions from industrial activities, together with improved urban waste management reducing the open burning of waste might have accounted for the observed $PM_{2.5}$ decline. Median ground-level ozone concentrations per year ranged from 64.36 – 105.37 µg m^{-3} which were in exceedance of the WHO guideline limit (Fig. 2A). The highest and lowest were recorded for the years 2021 and 2003 respectively. A trend of fluctuations and plateaus was observed for ozone concentrations across the 23-year duration. Noticeable plateaus in ozone concentrations were observed for the years, 2000 – 2001, 2006 – 2007, 2016 – 2017 and 2020 – 2021. Relatively rapid increases in ozone occurred from 2004 – 2006, 2009 – 2015. Notable decreases were observed from 2001 – 2004, 2007 – 2009 and 2015 – 2016. Furthermore, in the last few years (2021 – 2023), there has been a significant decrease in ozone levels following the peak in 2021. The variability in ground-level ozone levels may have been due to the complex interplay of factors such as fluctuating weather conditions, including temperature, humidity, and wind speed, which might have influenced the formation and dispersion of ozone. Also, anthropogenic activities such as industrial processes and transportation emissions might have contributed to ozone formation through the emission of precursor pollutants. The KT test indicated a strong positive correlation between years and O_3 concentration, with Kendall's tau coefficients (τ) of 0.6097 (τ_a) and 0.6229 (τ_β). In addition, a p-value < 0.0001 indicated a significant increasing trend in tropospheric O_3 concentration over the 23 years (Table S9). In addition, a positive slope coefficient β (0.61), a p-value < 0.001 and 95 % CI [0.59, 0.63] were obtained from the Sen's slope analysis (Table S10). These confirmed a consistently increasing trend in O_3 concentrations over the years in urban cities. This could have been due to the continuous decline in Nitrogen Oxides (NOx) accounting for an increase in the ratio of Volatile Organic Compounds (VOCs) to NOx. This might have favoured ozone formation in a NOx-limited regime through the suppression of ozone titration, increased radical activities and peroxide formation over nitric acid formation. In addition, higher temperatures increasing ozone production by rising emissions of precursors such as VOCs alongside higher solar radiation intensities in the study area might have accounted for the observed increase in tropospheric ozone.

Median NO_2 concentrations per year in the urban cities spanned from 6.41 – 8.18 µg m^{-3} below the WHO threshold (Fig. 4B). The lowest and highest concentrations were recorded in the years 2023 and 2005 respectively. A general trend of decreasing NO_2 concentrations was observed with variabilities in NO_2 concentrations from year to year as some years showed significant increases (2000 – 2005, 2010 – 2011, 2014 – 2015) or decreases (2005 – 2010, 2017 – 2019) compared to the preceding years, indicating fluctuations in NO_2 levels. The general declining trend in urban NO_2 concentrations appears to have stabilized in the most recent years (2021–2023), indicating that the trend may have slowed down or plateaued. Kendall's tau coefficients (τ) [-0.1192 (τ_a) and −0.1218 (τ_β)] and a p-value < 0.0001 indicated a weak negative correlation between years and NO_2 concentrations (Table S9). Furthermore, a negative slope coefficient β (-0.12), a p-value < 0.001 and 95 % CI [-0.15, −0.08] were obtained from the Sen's slope analysis (Table S10). These suggested a significant decreasing trend in NO_2 concentration over the years. This could be attributed to improved regulations of vehicular emissions and industrial processes through the adoption of cleaner energy alternatives, usage of catalytic converters in vehicles, improved public transit systems coupled with meteorological conditions such as dispersing wind patterns might have led to the decreasing trend in ambient urban NO_2 concentrations.

Comparing the annual concentrations of $PM_{2.5}$ in Ghanaian urban cities in this study to those in other global regions revealed notable differences (Table 3). Research by Tariq and colleagues (2023), and Mandal et al. (2020) reported higher concentrations in Niger and India respectively. The findings of Liu et al. (2023), Xu and Zhang (2020) and Rahman et al. (2021) reported a broader range of annual concentrations in urban Asian cities. In contrast, Park et al. (2020) reported a smaller range of annual concentrations in Seoul. Furthermore, Li et al. (2021) observed lower concentrations in Iraq and Kuwait. Azhari et al. (2021) also reported lower concentration ranges in Malaysia. Moreover, a local study by Bahino et al. (2024) reported notably lower concentrations in Accra, Ghana than this study.

Table 3

Comparison of concentrations of ambient urban air pollutants with comparative studies.

Reference	Location	Pollutant	Study Duration	Annual Concentrations
This Study	Ghana	$PM_{2.5}$	2000 – 2023	46.69 – 82.52 μg m^{-3}
Tariq et al. (2023)	Niger		1998 – 2019	68.85 – 70.47 μg m^{-3}
Liu et al. (2023)	China		2013 – 2021	6.5 – 94.2 μg m^{-3}
Xu and Zhang (2020)	Beijing, China		2013 – 2018	5 – 470 μg m^{-3}
Park et al. (2020)	Seoul, South Korea		2014 – 2015	41 – 46.7 μg m^{-3}
Mandal et al. (2020)	Delhi, India		2010 – 2016	87 – 138 μg m^{-3}
Li et al. (2021)	Iraq Kuwait		2001 – 2018	33 – 44 μg m^{-3} 36 – 49 μg m^{-3}
Azhari et al. (2021)	Kuala Lumpur, Malaysia		2019	30.4 – 43.7 μg m^{-3}
Rahman et al. (2021)	Dhaka, Bangladesh		2016	5.27 – 105 μg m^{-3}
Bahino et al. (2024)	Accra, Ghana		2020 – 2021	21.1 – 24.8 μg m^{-3}
This Study	Ghana	O_3	2000 – 2023	64.36 – 105.37 μg m^{-3}
He et al. (2023)	China		2013 – 2018	1.84 – 160 μg m^{-3}
McHugh et al. (2023)	Ireland		2010 – 2019	39 – 43 μg m^{-3}
Lee et al. (2023)	California, USA		2005 – 2017	94.08 – 103.88 μg m^{-3}
Huang et al. (2018)	China		2013 – 2017	141.0 – 163.5 μg m^{-3}
Xu et al. (2019)	Windsor, Canada		1996 – 2015	39.79 – 52.92 μg m^{-3}
This Study	Ghana	NO_2	2000 – 2023	6.41 – 8.18 μg m^{-3}
Jurado et al. (2020)	France		2013 – 2017	5 – 95 μg m^{-3}
Kuerban et al. (2020)	China		2015 – 2018	5.9–64.4 μg m^{-3}
Sanyal et al. (2018)	France		1999 – 2000	4.55 – 46.96 μg m^{-3}
Wang et al. (2022)	Accra, Ghana		2019 – 2020	70 μg m^{-3}
Wang et al. (2024)	Accra, Ghana		2019 – 2020	37 μg m^{-3}

The comparison of tropospheric ozone concentrations in the study with other studies in different geographical locations also revealed significant variability. The research conducted by He et al. (2023) reported wider concentration ranges compared to this study. The reported annual ranges in this study were above the reported levels of McHugh et al. (2023) and Xu et al. (2019). Higher and ground O_3 concentration ranges than this study's findings were observed by Huang et al. (2018) and Lee et al. (2023) in China. The annual nitrogen dioxide findings of this study were lower than the reported concentrations from related studies in France and China (Jurado et al., 2020; Sanyal et al., 2018; Kuerban et al., 2020). The differences in concentrations observed in this study could be due to its longer duration compared to related studies such as Wang et al. (2024) which had a shorter timeframe.

Principal Component Analysis (PCA) was employed in this study to determine spatial variability of air pollutants and the influence of each pollutant on principal components using three-factor loading categories; strong factors (> 0.75), moderate (0.50 – 0.75), and weak factors (< 0.50) (Ashong et al., 2024). The PCA revealed three principal components (total variance); PC1 (62.02 %), PC2 (22.72 %) and PC3 (15.26 %) in the study (Fig. 5). The first principal component (PC1) represented the most dominant air pollution pattern in the urban cities revealing an inverse relationship between $PM_{2.5}$ (- 0.61) and the gaseous pollutants; NO_2 (0.60) and O_3 (0.52). This could have been due to the prevalence of particulate emission sources (such as the combustion of solid fuels and dust from construction and mining activities) over gaseous pollutant sources. Also, finer $PM_{2.5}$ providing surfaces for heterogeneous reactions might have favoured the scavenging of gaseous pollutants in the atmosphere. The second principal component (PC2) characterized by a strong positive loading of O_3 (0.85) and a negative loading of NO_2 (- 0.45) indicated an inverse relationship between the two gaseous pollutants. This could be due to a non-linear photochemical ozone formation with NO_2 as a precursor in urban environs where higher solar radiation enhances ozone formation with lower NO_2 reducing ozone titration. This suggests PC2 represents photochemical processes governing ozone formation and depletion in the troposphere. The third principal component (PC3) showed strong positive loadings for both $PM_{2.5}$ (0.74) and NO_2 (0.67) with minimal influence from O_3 (0.1). This component likely represents localized pollution patterns and specific pollution sources affecting both $PM_{2.5}$ and NO_2 concentrations simultaneously. The co-variation of $PM_{2.5}$ and NO_2 in PC3 could be due to common pollution sources such as high traffic areas and industrial zones in urban cities.

The dominant role of PC1 suggests that air pollution mitigation strategies targeting $PM_{2.5}$ reduction may not proportionally affect NO_2 and O_3. Necessitating multi-pollutant approaches to addressing urban air pollution in Ghana. Furthermore, the distinct behaviour of O_3 in PC2 highlights the need for interventions tailored to target ozone formation particularly in urban areas prone to photochemical smog. In addition, PC3 suggests the possibility of some targeted interventions mitigating both $PM_{2.5}$ and NO_2 simultaneously in certain urban areas. The PCA biplot revealed southern urban cities exhibited elevated concentrations of $PM_{2.}$which could be attributed to higher vehicular traffic, industrial processes and combustion activities in southern Ghana. In contrast, northern urban cities had higher O_3 concentrations likely due to photochemical reactions involving NO_2 and VOC precursors under favourable conditions such as higher solar radiations in northern Ghana.

The population attributable fraction (%) (PAF) for air pollution is an epidemiologic measure which estimates the proportion of disease cases in a population that can be attributed to exposure to a specific air

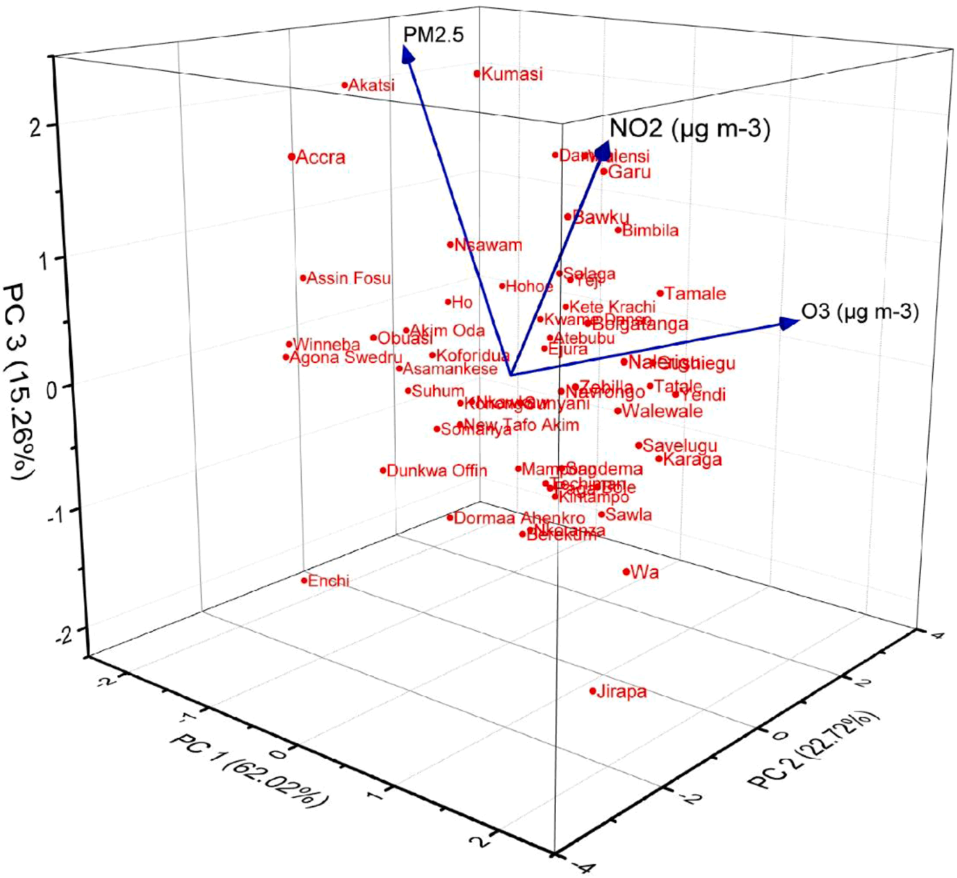

Fig. 5. Principal component analysis biplot of air pollutants in Ghanaian urban cities.

pollutant. Thus, it represents the percentage of disease burden in the population that could be avoided if exposure to the air pollutant were mitigated. The median PAF for annual air pollutant exposure in the urban cities is given in Table S11 and S12.The median PAF associated with ambient exposure to $PM_{2.5,}$ $O_{3,}$ and NO_2 in the urban cities varied from 14.25 – 34.61 %, 1.94 – 8.28 %, and 1.14 – 11.72 % respectively. The highest annual PAF for $PM_{2.5,}$ $O_{3,}$ and NO_2 exposure were observed for the years 2000, 2020 and 2005 respectively (Table S12). The Mann-Kendall test was used to examine the relationship between years and PAFs for $PM_{2.5}$, O_3, and NO_2. The obtained Kendall's tau coefficients (τ) [$PM_{2.5}$PAF = -0.1326 (τₐ) and −0.1366 (τ_β); NO_2PAF = -0.0804 (τₐ) and −0.0821 (τ_β)] revealed weak negative correlations for $PM_{2.5}$PAF and NO_2PAF with years (Table S12). Additionally, p-values < 0.0001 showed a significant decreasing trend in $PM_{2.5}$PAF and NO_2PAF over the years (Table S13). This suggested existing interventions in Ghana to tackle $PM_{2.5}$PAF and NO_2PAF were effective. In contrast, positive Kendall's tau coefficients (τ) [-0.1326 (τₐ) and −0.1366 (τ_β)] a p-value < 0.0001 were obtained for O_3PAF which indicated a significant increasing trend over the years. This indicated the need for targeted strategies to address O_3PAF in Ghana.

The epidemiological contribution of $PM_{2.5}$, NO_2, and O_3 to incidences, prevalences, mortalities, DALYs, YLLs and YLDs in Ghana were estimated for chronic respiratory diseases in general and specifically for COPD, pneumoconiosis, asthma, and ILSD. $PM_{2.5}$ had the highest incidence of respiratory diseases. CRD had the most cases at 63190, followed by asthma with 43296 cases. COPD and ILDS also recorded high incidences of 7019 and 12847 cases, respectively. PCN had the lowest incidence among the diseases, with only 28 cases attributed to $PM_{2.5}$ exposure. Exposure to ground-level ozone also resulted in the incidence of respiratory diseases albeit with a reduced impact compared to $PM_{2.5}$. CRD had the highest incidence (12667) followed by asthma (8679). COPD and ILDS had lower incidences of 1407 and 2575 cases, respectively. PCN registered the lowest incidence, with only 6 cases linked to ambient O_3 exposure. Nitrogen dioxide had the lowest incidence among the three air pollutants as CRD had the highest incidence at 9239 cases followed by asthma with 6331 cases. COPD and ILDS had lower incidences of 1026 and 1878 cases, respectively. PCN has the lowest incidence, with only 4 cases attributed to NO_2 exposure (Table S14). The estimated prevalence of CRD for annual $PM_{2.5}$ exposure was found to be 329880, which is significantly higher than the prevalence of COPD (115965), PCN (59), asthma (245644), and ILDS (1736). The prevalence of CRD due to O_3 exposure was estimated to be 66127, while that for NO_2 is 48233. The prevalence from ambient urban O_3 had estimates of 23246 for COPD, 12 for PCN, 43950 for asthma, and 348 for ILDS. NO_2 had the lowest prevalence among the three pollutants with prevalence of 16956 for COPD, 9 for PCN, 32057 for asthma, and 254 for ILDS (Table S15).

The estimated annual CRD mortalities varied from 1734 – 2185, 45 – 704, and 233 – 344 for ambient exposure to $PM_{2.5}$, $O_{3,}$ and NO_2 respectively. The average annual estimated deaths for COPD, pneumoconiosis, asthma, and ILSD from ambient $PM_{2.5}$ were 1079, 1, 696 and 42 respectively. Tropospheric ozone was estimated to account for 391, 216, 140 and 8 annual average mortalities in Ghana from CRD, COPD, asthma, and ILSD respectively. Furthermore, the ambient NO_2 in the study was found to result in 285, 158, 102 and 6 annual average mortalities in Ghana from CRD, COPD, asthma, and ILSD respectively. Estimates from the study indicated no mortalities for pneumoconiosis from O_3 and NO_2 ambient urban exposure in Ghana (Table S16). The annual DALY estimates revealed substantial impacts of the urban air pollutants on CRD, COPD, PCN, Asthma, and ILDS. It was observed that $PM_{2.5}$ consistently had the highest annual DALY average, generally for CRD (78653) and particularly for COPD (37933). These showed it significantly exacerbated CRDs in comparison with the other pollutants in Ghana. Annual average DALYs of 11500 (NO_2) and 15767 (O_3) were observed for CRD. In addition, DALYs linked to COPs were 7604 and 5546 for O_3 and NO_2 respectively (Table S17).

The obtained annual average YLL from CRD, COPD, PCN asthma, and ILSD ranged from 34 – 53938, 7 – 10812, 5 – 7887, for $PM_{2.5}$, $O_{3,}$ and NO_2 ambient exposure respectively. The highest and lowest YLLs were observed for CRD and PCN respectively. The highest YLLs for all the diseases were consistently associated with ambient $PM_{2.5}$ in the urban cities (Table S18). The highest and lowest annual YLD averages were observed for CRD (24715) and particularly for COPD (13456) respectively. The YLD estimates from the study indicated $PM_{2.5}$ had the most substantial impact on YLD, with notably high YLDs for CPD (24715), COPD (13456), asthma (8664) and ILDS (197). In comparison, O_3 recorded lower YLDs for CRD (4954), COPD (2697), asthma (1737), and ILDS (40). On the other hand, NO_2 registered the lowest YLDs for CRD (3614), COPD (1967), asthma (1267) and ILDS (29) among the three pollutants. The YLD estimates for pneumoconiosis associated with exposure to the three pollutants were < 10 (Table S19).

The epidemiological contribution of $PM_{2.5}$, $O_{3,}$ and NO_2 to CRD in Ghana revealed a significant public health burden with $PM_{2.5}$ consistently showing the highest impact across all health outcomes. The clear hierarchy of impact for incidence, prevalence, mortality, DALY, YLD and YLL in Ghana was $PM_{2.5} > O_3 > NO_2$. Notably, CRD bore the highest brunt of air pollution effects while PCN had minimal impact. These suggest the need for stricter $PM_{2.5}$ targeted reduction policies and the adequate resourcing of the Ghanaian health care system to improve the early detection, management and treatment of CRDs to reduce mortalities.

The ambient air pollutant concentrations in the urban cities were indexed using the corresponding estimated sub-indices (Q) for each air pollutant in the cities. The air quality index of the towns was obtained from the worst sub-indices. The estimated air quality indices and sub-air quality indices are provided in Table 4.

The $PM_{2.5}$ sub-air quality indices (121.25 – 152.43) rated the ambient concentrations in 56 urban cities as moderately good for human exposure while that of Akatsi was unhealthy. The sub-indices of NO_2 (2.34 – 6.09) and tropospheric O_3 (34.11 – 43.74) revealed the concentrations in all the urban cities were good for breathing. Overall, the air quality indices of 56 urban cities were found to be unhealthy for sensitive groups and that of Akatsi was unhealthy for all groups of people.

The $PM_{2.5}$ sub-air quality indices per annum rated its ambient pollution in urban cities as moderately good for breathing during the years 2001–2003, 2005–2006, 2009–2014, and 2018–2023. However, $PM_{2.5}$ sub-air quality indices per annum rated its pollution of the ambient air in the urban cities during the years 2000, 2004, 2007–2008, and 2015–2017 as unhealthy for breathing. Furthermore, NO_2 and O_3 sub-air quality indices per year indicated their pollution in the urban cities during the years 2000–2023 to be good for breathing. The years 2000, 2004, 2007 – 2008, and 2015 – 2017 had air quality indices indicating the ambient air of Ghanaian urban cities was unhealthy for breathing while that of the other years in this study's duration was unhealthy for sensitive groups (Table S20).

3.2. *Carcinogenic, non-carcinogenic, relative and excess health risk assessments of ambient air pollutant concentrations in urban cities*

The Hazard Quotients (HQ) for one-hour exposure in the urban cities were < 1 for all demographics, ranging from 0.49 – 0.50 for $PM_{2.5}$, 0.058 – 0.059 for O_3 and 0.032 – 0.033 for NO_2. The hazard indices (HI) [0.58 – 0.59] for the different age groups were below the threshold of 1, denoting no significant non-carcinogenic risks from one hour of exposure to the air pollutants. HQ values ranging from 1.47 – 1.49 for $PM_{2.5}$, 0.096 – 0.099 for NO_2 and 0.175 – 0.177 for O_3 were obtained for three hours of exposure across all age groups. Non-carcinogenic HI of 1.73–1.75 indicated significant risks for three-hour exposure to ambient air pollution in the cities. For six hours of exposure to $PM_{2.5}$ HQ values of 2.94–2.97 were observed whereas HQ values of 0.19 – 0.20 and 0.350 – 0.353 were obtained for NO_2 and O_3 respectively. Non-carcinogenic HI ranging from 1.18 – 3.51 revealed significant non-cancer risks for six-hour exposure. Nine-hour exposure had a non-carcinogenic HQ of 4.41 – 4.46 for $PM_{2.5}$, 0.288 – 0.295 NO_2 and 0.52 – 0.53 for O_3 exposure. Non-carcinogenic HI of 5.20–5.26 was obtained for nine-hour exposure to the air pollutants. Worst-case scenario assessments gave HQ values of 5.88 – 5.94 for half-day and 11.76 – 11.88 for full-day adult ambient exposure to $PM_{2.5}$. The HQ values for O_3 and NO_2 half-day exposure were < 1. HQ values > 1 (1.39 – 1.41) were obtained for full-day ambient exposure to O_3 while the HQ values of 0.77 – 0.79 were obtained for NO_2. Significant non-carcinogenic deleterious risks with HI ranging from 6.94 – 7.01 for half-day and 13.96 – 14.03 for full-day exposure were observed in this study for all the different age groups (Table S21).

Slight differences were observed between the different age groups regarding potential non-carcinogenic risks to ambient air pollutants. The non-carcinogenic risks from both $PM_{2.5}$ and NO_2 exposure in the urban cities could be ranked in descending order as Toddlers $>$ Children $>$ Infants $>$ Adults $>$ Adolescents while that for O_3 was Children $>$Toddlers $>$ Infants $>$ Adults $>$ Adolescents. This suggested that younger age groups such as children and toddlers are more susceptible to adverse non-cancer effects from urban air pollution in Ghana. The individual contribution of the air pollutants to non-cancer risks in this study could be ranked in descending order as $PM_{2.5} > O_3 > NO_2$. The findings of the study suggest that traders, auto-artisans, farmers, masons, traffic wardens, street hawkers and other outdoor workers who quotidianly spend three to nine hours in ambient environs performing their occupational activities in urban cities in the country are more vulnerable to non-cancer health risks. Furthermore, the exposure of sensitive groups (such as people with pre-existing lung and cardiovascular diseases) for three hours and beyond could lead to the exacerbation of pre-existing health conditions.

The carcinogenic risks (CR) for human exposure to $PM_{2.5}$ concentrations in urban cities ranged from 2.82E-06–6.76E-05 for adults, 3.95E-06–9.48E-05 for adolescents, 1.44E-05–3.44E-04 for children, 1.13E-04–2.72E-03 for infants and 3.67E-05–8.80E-04 for toddlers. These indicated acceptable carcinogenic risks for adults, adolescents, children and toddlers as the CR were within the tolerable carcinogenic risk limit of 1E-04–1E-06. Contrarily, the CR for infants' exposure to ambient $PM_{2.5}$ concentrations in urban cities indicated significant carcinogenic risks CR for an exposure time of nine hours and beyond (Table S22).

The estimated relative and excess risks obtained for the concentrations of ambient air pollutants in the urban cities are provided in Table S23. The relative risks for $PM_{2.5}$ and O_3 in the 57 urban cities in the study were > 1 and the respective excess risks were positive. These both suggested concentrations of $PM_{2.5}$ and O_3 in the ambient air of the cities posed significant health risks to the dwellers thereof. Except for Wa, Walewale, Tamale, Navrongo, Garu, Gushiegu, Bolgatanga, Bawku, Accra, Kumasi and Nalerigu the relative risks for $NO_2 < 1$ and the corresponding excess risks were negative. These both indicated ambient concentrations of NO_2 in most of the urban cities posed no significant health risks. The excess risks for $PM_{2.5}$, O_3 and NO_2 in the urban cities varied from 0.0176 – 0.0242, 0.0059–0.0158 and (-) 0.0082 to (+) 0.0028 respectively.

Furthermore, the relative risks for $PM_{2.5}$ and O_3 for annual concentrations per annum were > 1 which indicated they posed significant risks to the health of urban habitants in Ghana from 2000 – 2023. In contrast, the relative risks for concentrations of NO_2 per year were < 1 suggesting no significant health risks from its exposure. The excess risks for $PM_{2.5}$, O_3 and NO_2 per annum varied from 0.0160 to 0.0299, 0.0030–0.0222 and (-) 0.0024 to (-) 0.0046 respectively (Table S24).

Table 4
Classification of air quality index of ghanaian urban cities.

City	$QPM_{2.5}$	QO_3	QNO_2	AQI
Accra	142.19	34.11	5.56	Unhealthy for Sensitive Groups
Agona Swedru	145.24	34.50	3.14	Unhealthy for Sensitive Groups
Akatsi	152.43	37.07	3.49	Unhealthy
Akim Oda	143.96	37.83	3.34	Unhealthy for Sensitive Groups
Asamankese	146.10	38.07	2.48	Unhealthy for Sensitive Groups
Assin Fosu	148.82	35.34	3.08	Unhealthy for Sensitive Groups
Atebubu	143.17	42.21	3.00	Unhealthy for Sensitive Groups
Bawku	135.87	40.59	5.74	Unhealthy for Sensitive Groups
Berekum	130.95	39.68	3.95	Unhealthy for Sensitive Groups
Bimbila	141.68	43.46	4.23	Unhealthy for Sensitive Groups
Bole	131.84	41.94	3.97	Unhealthy for Sensitive Groups
Bolgatanga	132.17	40.83	5.57	Unhealthy for Sensitive Groups
Cape Coast	139.90	-	1.83	Unhealthy for Sensitive Groups
Dambai	148.35	42.59	3.69	Unhealthy for Sensitive Groups
Dormaa Ahenkro	134.73	38.18	3.42	Unhealthy for Sensitive Groups
Dunkwa Offin	140.46	36.95	2.76	Unhealthy for Sensitive Groups
Ejura	139.94	41.39	3.65	Unhealthy for Sensitive Groups
Enchi	138.25	34.48	2.36	Unhealthy for Sensitive Groups
Garu	135.58	41.32	6.09	Unhealthy for Sensitive Groups
Gushiegu	132.05	42.94	5.03	Unhealthy for Sensitive Groups
Ho	146.42	39.44	2.95	Unhealthy for Sensitive Groups
Hohoe	147.72	41.34	2.66	Unhealthy for Sensitive Groups
Jirapa	121.25	40.35	4.56	Unhealthy for Sensitive Groups
Karaga	128.53	42.79	4.90	Unhealthy for Sensitive Groups
Kete Krachi	143.13	42.56	3.28	Unhealthy for Sensitive Groups
Kintampo	135.91	41.62	2.98	Unhealthy for Sensitive Groups
Koforidua	141.62	38.31	3.54	Unhealthy for Sensitive Groups
Konongo	139.24	38.89	3.51	Unhealthy for Sensitive Groups
Kumasi	145.57	39.41	5.16	Unhealthy for Sensitive Groups
Kwame Danso	143.74	41.94	3.09	Unhealthy for Sensitive Groups
Mampong	137.03	40.54	3.15	Unhealthy for Sensitive Groups
Nalerigu	129.14	41.33	5.81	Unhealthy for Sensitive Groups
Navrongo	132.45	40.47	4.92	Unhealthy for Sensitive Groups
New Tafo Akim	139.43	39.00	3.24	Unhealthy for Sensitive Groups
Nkawkaw	140.22	39.44	3.25	Unhealthy for Sensitive Groups
Nkoranza	134.97	40.78	2.93	Unhealthy for Sensitive Groups
Nsawam	143.98	38.91	4.04	Unhealthy for Sensitive Groups
Obuasi	142.19	36.61	3.75	Unhealthy for Sensitive Groups
Paga	130.56	40.19	4.44	Unhealthy for Sensitive Groups
Salaga	143.37	42.23	3.59	Unhealthy for Sensitive Groups
Sandema	131.17	40.57	4.46	Unhealthy for Sensitive Groups
Savelugu	130.71	42.68	4.56	Unhealthy for Sensitive Groups
Sawla	131.36	42.12	3.77	Unhealthy for Sensitive Groups
Somanya	140.38	38.47	3.05	Unhealthy for Sensitive Groups
Suhum	143.49	37.99	2.82	Unhealthy for Sensitive Groups
Sunyani	133.98	39.66	4.58	Unhealthy for Sensitive Groups
Sekondi-Takoradi	137.94	-	2.34	Unhealthy for Sensitive Groups
Tamale	133.88	43.19	5.25	Unhealthy for Sensitive Groups
Tatale	134.87	43.74	4.12	Unhealthy for Sensitive Groups
Techiman	133.82	40.77	3.69	Unhealthy for Sensitive Groups
Wa	122.78	40.99	5.33	Unhealthy for Sensitive Groups
Walewale	130.20	41.69	5.10	Unhealthy for Sensitive Groups
Winneba	146.71	34.76	2.92	Unhealthy for Sensitive Groups
Wulensi	146.42	43.10	4.00	Unhealthy for Sensitive Groups
Yeji	142.62	42.45	3.66	Unhealthy for Sensitive Groups
Yendi	131.05	43.56	4.88	Unhealthy for Sensitive Groups
Zebilla	132.49	40.86	4.92	Unhealthy for Sensitive Groups

Where Q = sub-air quality index, AQI = Air Quality Index, Green Colour = Good, Orange Colour = Unhealthy for Sensitive Groups and Red Colour = Unhealthy,

3.3. Limitations

A notable limitation of this study is that the impact of seasonal regional dust storms on the concentrations of pollutants for the study's duration was not assessed. This is due to the lack of ground and satellite harmattan and non-harmattan pollutant measurements in the urban cities. Furthermore, the lack of data on VOCs concentrations limited the study from assessing the ratio of VOC to NOx to shed further light on potential sources of ground-level ozone in the cities for the two decades. Moreover, the concentrations of pollutants in the study are based on satellite measurements, and the dearth of ground measurements of the pollutants for the study's duration prevented the study from comparing these satellite measurements with annual ground-monitored concentrations. In addition, the forecasting of air pollution in the study did not account for the impact of the COVID-19 lockdowns on air pollution trends in the country.

3.4. Policy suggestions

Efficient ground monitoring and reporting of real-time urban air quality along with strict enforcement of air quality standards as outlined by the WHO and Ghana's EPA are needed to safeguard the public's health. Rapid transition to renewable energy, promotion of electric vehicles, improved public transportation and stricter emissions controls and incentives are essential globally, including in Ghana.

Effective air quality management plans should be implemented in Ghana's urban cities. These should include reducing emissions from transportation, industry, and waste burning. They should also promote clean cooking technologies, enhance transportation infrastructure and encourage ecologically conscious development. Ghana must strengthen its regulatory framework by imposing stringent emission limits on vehicles, industry and other significant polluters. Enhancing the capacity of regulatory bodies to oversee, document and enforce adherence to air quality guidelines is crucial.

Local governments and communities should receive training and resources to create effective air quality management plans, alongside international collaboration for sharing best practices and technical support. Ghana should foster cooperation between educational institutions, public and private organizations, and businesses to develop innovative solutions for regional air pollution focusing on health impacts. National budgets, foreign donations and private sector investments should fund initiatives to improve air quality, along with financial incentives for adopting greener practices and technologies. Public health campaigns are needed nationwide to increase the awareness of residents of urban cities on air pollution and its significant impact on their health.

4. Conclusion

The development in urbanization, population, and industrialization has significantly increased ambient air pollution in urban cities both locally and globally causing some of the most serious air quality challenges. The comprehensive health risk evaluation of ambient air pollution in urban areas in Ghanaian cities from 2000 to 2023 revealed significant findings.

The findings showed that with significant regional variations, the yearly median $PM_{2.5}$ concentrations being the most detrimental overall for chronic respiratory diseases such as asthma, were five to six times higher than WHO recommendations. Compared to northern cities, Accra, Koforidua, and Kumasi consistently showed higher $PM_{2.5}$ levels. Ozone and NO_2 concentrations also varied and periodically surpassed recommended thresholds.

Most urban cities had a dominant $PM_{2.5}$-O_3 pollution profile, which suggests significant health risks. Severe health risks are highlighted by high median population attributable fractions (PAF) for air pollution exposure especially for $PM_{2.5}$. Hazard indices from $PM_{2.5}$ exposure through inhalation indicated significant non-cancer health risks for an exposure duration of three hours and beyond per day. Carcinogenic risks for human exposure to urban $PM_{2.5}$ concentrations were mostly within the acceptable limit of 1E-04–1E-06.

The air quality indices of 56 urban cities were found to be unhealthy for sensitive groups and that of Akatsi was unhealthy for all groups of people. Urban air quality indices show moderately good ambient pollution from 2001 to 2003, 2005–2006, 2009–2014, and 2018–2023, with unhealthy pollution from 2000 to 2017, and good sub-air quality from 2000 to 2023. Relative risks > 1 for $PM_{2.5}$ and O_3 confirmed substantial health risks for urban residents with $PM_{2.5}$ pollution contributing to a reduction in life expectancy by 4.5–6.2 years.

Regarding the severe adverse health effects of $PM_{2.5}$ and O_3 pollution, this study highlights the urgent need for focused actions to enhance air quality in Ghanaian metropolitan areas. For an in-depth awareness of air pollution dynamics in Ghana and West Africa, future studies should prioritize bridging data gaps, including the effects of periodic dust storms and volatile organic compounds levels.

CRediT authorship contribution statement

Marian Asantewah Nkansah: Writing – review & editing, Validation, Supervision, Project administration. **Nana Kwabena Oduro Darko:** Writing – review & editing, Validation. **Blessed Adjei Yeboah:** Writing – review & editing, Software, Investigation, Data curation. **Maame Serwaa Boapea:** Writing – review & editing, Validation, Investigation. **Thomas Peprah Agyekum:** Writing – review & editing, Supervision, Project administration, Formal analysis, Data curation, Conceptualization. **Meshach Kojo Appiah:** Writing – review & editing, Visualization, Formal analysis. **Birago Adu Ababio:** Writing – review & editing, Visualization, Formal analysis. **Gerheart Winfred Ashong:** Writing – review & editing, Validation, Methodology, Formal analysis. **Lorenda Sarbeng:** Writing – review & editing, Visualization, Software. **Boansi Adu Ababio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eldad Boansi:** Writing – review & editing, Validation, Conceptualization. **Felix Adulley:** Writing – review & editing, Validation, Investigation. **Kwabena Dabie:** Writing – review & editing, Validation, Methodology. **Edward Ebow Kwaansa-Ansah:** Writing – review & editing, Validation, Supervision, Project administration. **Michael Kweku Commeh:** Writing – review & editing, Supervision, Project administration. **Jonathan Nartey Hogarh:** Writing – review & editing, Supervision, Project administration.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2024.117591.

Data availability

Data will be made available on request.

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