

Research Article



Seasonal Variation of Tropospheric Air Pollutants and Their Association with Meteorological Parameters over Nigeria

Moses Audu^{1*}, Agada Ojochenemi¹, Francisca Okeke², Shelle Benedict¹, Atuha Tersue¹

¹Department of Physics, Joseph Sarwuan Tarka University, P.M.B. 2373, Nigeria

²Department of Physics and Astronomy, University of Nigeria, P.M.B. 410001, Nigeria

* Correspondence: audu.moses@uam.edu.ng

Received: 19 May 2025 / Accepted: 25 August 2025 / Published: 07 September 2025

Abstract: Air pollution is a major environmental issue that is of significant concern globally, due to its detrimental health impacts. The impacts of air pollution depend on several factors. For effective air quality management, the effect of meteorological factors on air pollutants is crucial. This study, therefore, investigates this influence across Nigeria using data on air pollutants: carbon monoxide (CO), nitrogen dioxide (NO₂), methane (CH₄), ozone (O₃), and formaldehyde (HCHO), and meteorological variables: maximum temperature (T_{max}), minimum temperature (T_{min}), precipitation (PRCP), wind speed, and cloud cover from Sentinel-5P TROPOMI and Climatic Research Unit. The study covered November 2018 to December 2023 (2018–2023). Hierarchical cluster and Pearson correlation analyses were applied. Seasonally, both tropospheric air pollutants and climatic parameters varied from one month to another. Pollutants showed similar seasonal patterns except O₃; however, their concentrations differed from month to month. Our findings show relationships between climatic parameters and pollutants, but the significance and direction varied with the pollutant and the parameter. This suggests that the influence of climatic parameters on pollutants depends on both the parameter and the pollutant considered. This study provides scientific insight for effective air quality management.

Keywords: air pollutants, atmospheric parameters, seasonal distribution, cluster analysis, air quality

INTRODUCTION

Air pollution is a major environmental issue that is of significant concern globally, because of its detrimental health impacts. It is one of the major environmental problems in urban areas. Densely populated areas are particularly vulnerable due to increased road traffic, concentration of emission sources, industrial activities, power generation, instability of the atmosphere, etc. (Anderson, 2009). Air pollution poses a significant threat to human health and well-being as well as the environment (Agarwal et al., 2006).

Air pollutants can be emitted directly from the emission sources (primary pollutants) or formed through chemical reactions in the air (secondary pollutants). Key pollutants are ozone (O₃), carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), particulate matter (PM), and volatile organic compounds (VOCs). Sources of these pollutants include human activities (combustion of fossil fuels, traffic exhaust, power generation, industrial processes, and agriculture) and natural sources (wildfires, volcanic eruptions, dust storms, and biological processes).

The effects of air pollution on human health, ecosystems, and the global climate depend on meteorological factors, exposure time, chemical composition, and concentration of pollutants, among others. For instance, O₃ and NO₂ can cause asthma, bronchitis, lung cancer, and even premature death (Curtis et al., 2006). SO₂ and NO₂ can cause acid rain, which affects ecosystems and biodiversity. This can lead to acidification of soils and water bodies, which are harmful to aquatic life and forest health (Likens, 2021). Tropospheric O₃ can damage crop yield leading to food shortage (Mills et al., 2018; Sicard et al., 2020; Mahmud et al., 2023). CO₂ and CH₄ are greenhouse gases that contribute to global warming and climate change by trapping heat radiated from the Earth's surface and preventing it from escaping into space. These effects of air pollution, however, vary from short-term to long-term.

Meteorological parameters (temperature, cloud cover, wind speed and direction, etc.) and atmospheric stability have been reported to influence pollutant formation, dispersion, movement, and dilution of pollutants through the atmosphere (Beamish et al., 2011). For effective air quality management,

the interplay between air pollutants and meteorological factors is very crucial (Bobak, 2000). Several studies have been carried out to understand the complex interplay between meteorological factors and pollutant dispersion across the globe, including Nigeria. Assessment of air pollution and air quality has been carried out in different regions of Nigeria (Akinfolarin et al., 2018; Okimiji et al., 2021; Daful et al., 2020; Omoko et al., 2021; Amanabo and Umaru, 2022; Atubi and Osoyibo, 2020; Onwosi and Nymphas, 2022; Chukwu et al., 2022; Abulude et al., 2022; Omokpariola et al., 2024). Omoko et al. (2021) reported high concentrations of pollutants in Southeastern Nigeria. They noted that air quality in the area was poor and needed to be monitored regularly.

Working on air quality parameters (particulate matter, gaseous pollutants, relative humidity, and temperature) in Port Harcourt, Akinfolarin et al. (2018) reported that the emerging industrial areas might not be responsible for the emissions of the soot observed in the study area. Amanabo and Umaru (2022) concluded from their study on ambient air quality assessment for three criteria air pollutants that air quality monitoring should be considered a priority for urban and rural areas.

Investigating the relationship between air pollutants (CO_2 , NO_2 , SO_2 , VOCs, $\text{PM}_{2.5}$) and meteorological parameters (temperature, relative humidity, atmospheric pressure) for three slum settlements, Okimiji et al. (2021) observed a positive correlation between CO_2 and temperature but an inverse relationship between relative humidity and $\text{PM}_{2.5}$. Similarly, Onwosi and Nymphas (2022) found a strong correlation between CO_2 and temperature, as well as NO_2 and wind speed from their study.

Despite these studies on air pollution and the relationship between air pollutants and meteorological parameters in the country, further studies are needed. Worthy of note is that Okimiji et al. (2021), who worked on the relationship between air pollutants and meteorological parameters considered three coastal slum settlements in Lagos, whereas Onwosi and Nymphas (2022) and Atubi and Osoyibo (2020) focused on Delta State and Vincent et al. (2017) considered major traffic corridors in Port Harcourt. Such localized studies may not give a national view of the relationship between air pollutants and meteorological parameters over the country. This study addresses that research gap by examining the seasonal pattern of tropospheric air pollutants and the influence of climatic parameters on their seasonal distribution across the country. The results of this study could serve as a reference for future studies, especially in Nigeria.

Nigeria is located in West Africa with geographical coordinates of 4° to 14° N latitude and 2° to 15° E longitude. The population of the country is approximately 202 million people. The tropical climate experienced in the country is characterized by two main seasons: wet (April–October) and dry (November–March). Meteorological parameters (humidity, wind speed, atmospheric pressure, etc.) vary across the country from the coastal region to the northern region depending on the interplay of the air masses that control the atmospheric conditions of the country. Air pollution in the country has been increasing, especially in urban areas due to increased vehicular emissions, urbanization, power generation, and industrialization (Mahmud et al., 2023).

Nigeria's air pollution dynamics are distinct from those of other regions. This could be due to high oil exploitation and production, oil bunkering, gas flaring, oil explosions, and other anthropogenic activities, which are major sources of pollutant emissions in the country, leading to poor air quality that falls below the World Health Organization's recommendations (Okoro et al., 2023). This suggests the need for continuous monitoring of air pollutants nationwide.

In this study, we used satellite-derived air pollutant dataset from the TROPOspheric Monitoring Instrument (TROPOMI) with a spatial resolution of $3.5 \text{ km} \times 5.5 \text{ km}$ (Veefkind et al., 2012). Theoretical analyses have been carried out on the uncertainties of this dataset as well as comparative validations (see Li et al., 2025 for more details). The use of satellite-derived datasets is largely due to limitations associated with ground-based measurement of meteorological parameters and air pollutants in the country, because the available datasets are not freely accessible and are costly. Generally, ground monitoring and measurements are often limited in spatial and temporal coverage (Li et al., 2025); while satellite remote sensing provides data with high spatial and temporal resolution at regional and global scales (Okoro et al., 2023). Therefore, most studies employ satellite data because they offer high spatial and temporal resolution, consistency, ready availability, and free access.

It is pertinent to note that studies on the validation of satellite data with ground monitor datasets have been carried out in Nigeria, with slight variations reported (Olomiyesan & Oyedum, 2016; Datti et al., 2024). For instance, comparing ground-measured data of solar radiation from the Nigerian Meteorological Agency (NiMet) and satellite-derived data from the National Aeronautics and Space Administration (NASA) for the North-Western region of Nigeria, Olomiyesan & Oyedum (2016) observed slight variation across the region based on the observed percentage error between the two

datasets. Thus, several scholars have employed satellite observation data of atmospheric parameters and pollutants in their studies (Olomiyesan & Oyedum, 2016; Okoro et al., 2023).

Worth mentioning is the reduction of air pollutants during the COVID-19 pandemic. During the lockdown, significant reductions in pollutant concentrations were reported worldwide (Olatunde & Ajayi, 2020; Adeyemi et al., 2021; Odediran et al., 2022). These reductions were due to the decreased emission of pollutants from both point and line sources such as industrial activities and vehicle operations. The effect of the decrease observed during the lockdown may be negligible relative to the period under investigation (November 2018–December 2023), since the lockdown lasted for less than two months in the country (30 March–15 May 2020) and monthly mean daily concentrations of air pollutants were used in this study.

METHOD

Monthly mean daily CO, NO₂, CH₄, O₃, and HCHO provided by Sentinel-5P TROPOMI offline Level 3 (OFFL/L3) downloaded from the Copernicus Data Space Ecosystem (<https://dataspace.copernicus.eu/>; accessed on 30 January 2025) and maximum temperature (Tmax), minimum temperature (Tmin), precipitation (PRCP), wind speed, and cloud cover from the Climatic Research Unit gridded Time Series (CRU TS 4.08; University of East Anglia, Norwich, United Kingdom) were used in this study. This study spanned from November 2018 to December 2023.

The following methods were employed in data analysis. Google Earth Engine was used to extract air pollutants data from Sentinel-5P TROPOMI in GeoTiff format using the geographic extent of Nigeria. The data were then converted into raster and thereafter into CSV format using ArcGIS 10.8. R software was used to extract meteorological data for Nigeria from CRU in CSV format. Monthly averages of both air pollutants and climatic parameters were then computed. The corresponding monthly percentage variation was also computed. Bar charts were then plotted to visualize of the monthly variation of pollutant concentrations and climatic parameters. Hierarchical cluster analysis was performed using Ward's linkage method to assess the relation between the air pollutants and the climatic variables. To ascertain the strength and direction of the relationship, Pearson correlation analysis was performed at $p < 0.01$ and $p < 0.05$ using SPSS software.

RESULTS & DISCUSSION

Monthly Mean Daily Variation of Air Pollutants and Climatic Variables (2018–2023)

Figure 1(i) shows that the concentration of CO was high during the dry season (i.e., November–March), but low during the rainy season (i.e., April–October). Similar variation patterns were observed for other pollutants (i.e., NO₂, CH₄, and HCHO) except O₃, which was high during the rainy season and low during the dry season (Figure 1(ii-iv)). During the dry season, the highest percentage concentrations of 10.2 %, 12.5 %, 8.38 %, and 11.8 % for CO, NO₂, CH₄, and HCHO were observed in March, except for NO₂, which was observed in January. On the other hand, during the rainy season, the lowest percentage concentrations of 6.8 %, 5.4 %, 8.27 %, and 4.4 % for CO, NO₂, CH₄, and HCHO were observed in September, October, July, and August respectively.

On the contrary, the highest and lowest percentage concentrations of 8.7 % and 7.8 % were observed for O₃ during the rainy season (July and August) and dry season (January and December) respectively (Figure 1(v)). This variation could be attributed to O₃ formation from other pollutants (i.e., precursor pollutants). Tropospheric ozone is formed from photochemical reaction of nitrogen oxides and volatile organic compounds (Alonso et al., 2025). Thus, it is considered a secondary pollutant. Generally, our observations show that air pollutants may have similar variation patterns; however, their concentrations varied from one month to another. This could be attributed to their sources and to factors such as meteorology, dispersion, and chemical transformation (Zhao et al., 2021).

Similarly, wind speed, Tmax, and Tmin were high during the dry season but low during the rainy season, whereas the reverse is true for cloud cover and PRCP (Figures 1(vi) and 2). The highest percentages (9.2 %, 9.2 %, and 9.1 %) and lowest (6.5 %, 7.4 %, and 7.2 %) for wind speed, Tmax, and Tmin were observed during dry season (April, March, and April) and during rainy season (October, August, and December / January) respectively. On the other hand, the highest percentages of 10.4 % and 18.1 % for cloud cover and PRCP were recorded in August and September, while the lowest percentages of 6.8 % and 0.5 % were observed in November/December and January respectively. This implies that the climatic parameters also vary seasonally from one month to another, suggesting a possible relationship between air pollutants and climatic variables. To ascertain the significance of this relationship for the period under study, we employed cluster and correlation analyses.

It is interesting to note that the high and low concentrations of HCHO observed in March, April, and May (dry season) and June, August, and September (rainy season), respectively, in this study are in contrast to the highest and lowest HCHO concentrations reported in summer (June, July, and August) and spring (March, April, and May) over North China by [Li et al. \(2025\)](#). This could be attributed to the atmospheric condition of the study area and other factors that influence the formation, transportation, and dispersion of pollutants.

Dendrogram Cluster of Air Pollutants and Climatic Variables

Figure 3(i–v) presents the dendrogram cluster of CO, NO₂, CH₄, HCHO, and O₃ with climatic variables while Figure 3(vi) shows the dendrogram cluster for climatic variables. From the dendrogram cluster of air pollutants and climatic variables, two clusters were distinguished (Figure 3). The dendrogram of CO and the climatic variables shows that the first cluster is composed of PRCP, cloud cover, and T_{min} (Figure 3(i)). Similar patterns are seen in the clusters of NO₂, CH₄, and HCHO with the climatic variables, except for the cluster of O₃, in which the first cluster is composed of PRCP, cloud cover, O₃, and T_{min} (Figure 3(i–v)). The compositions of the second clusters are CO, T_{max}, and wind speed (Figure 3(ii)), NO₂, wind speed, and T_{max} (Figure 3(ii)), CH₄, T_{max}, and wind speed (Figure 3(iii)), HCHO, T_{max}, and wind speed (Figure 3(iv)), and T_{max} and wind speed (Figure 3(v)). This depicts that T_{max} and wind speed could have a strong relation with all the pollutants, since they appear in second cluster of all the pollutants except the second cluster of O₃.

Thus, we suggest that among the climatic parameters considered, T_{max} and wind speed could have more influence on the seasonal variation of air pollutants (that is, in dispersion, transformations of pollutants, etc.) compared with the other parameters. [Ahmadi et al. \(2015\)](#) reported from their study that temperature and wind speed have greater effects on pollutants than other parameters because they increased pollutant concentrations. Assessing air pollutant concentrations (VOC, NO₂, CO₂, PM_{2.5}, and SO₂) and meteorological parameters (atmospheric pressure, temperature, and relative humidity) in Lagos, [Okimiji et al. \(2021\)](#) reported that the major meteorological parameters affecting the air pollutants are atmospheric pressure, temperature, and relative humidity.

Worthy of note is the dendrogram cluster of O₃ with the climatic parameters (Figure 3(v)). It is seen that the first cluster is composed of PRCP, cloud cover, O₃, and T_{min} while the second cluster is composed of T_{max} and wind speed. This implies a good relationship between O₃ and PRCP, cloud cover, and T_{min} as compared to T_{max} and wind speed. This suggests that PRCP, cloud cover, and T_{min} could have more influence on O₃ than T_{max} and wind speed.

From the dendrogram cluster of climatic parameters (Figure 3(vi)), the first cluster shows that among the climatic parameters, T_{max}, T_{min}, and wind speed tend to be related, which is linked to cloud cover. The second cluster presents PRCP which is however linked to the first cluster. Furthermore, the correlation matrix of gaseous pollutants and climatic variables was analyzed using Pearson correlation for more insight.

Correlation Matrix of Air Pollutants and Climatic Variables

Correlation Matrix of Air Pollutants

The correlation matrix of air pollutants depicts a strong positive correlation of 0.783, 0.860, and 0.728 for CO–NO₂, CO–HCHO, and NO₂–HCHO at $p < 0.01$ and a strong positive correlation of 0.600 for CH₄–HCHO at $p < 0.05$. Strong negative correlations of -0.723 and -0.890 were observed for CO–O₃ and NO₂–O₃ at $p < 0.01$ and a strong negative correlation of -0.658 for O₃–HCHO at $p < 0.05$. Weak positive correlations of 0.419 and 0.135 were observed for CO–CH₄ and NO₂–CH₄ and a weak negative correlation of -0.387 for CH₄–O₃. This implies that relationships exist among pollutants, which is consistent with earlier findings (e.g., [Mahmud et al., 2023](#)); however, the significance of the correlation varied based on the concentration of pollutants in the study area. The observed correlation could be attributed to the emission sources. This suggests that pollutants from the same sources may be correlated with each other. According to [Mahmud et al. \(2023\)](#), pollutants are mainly emitted from fossil fuel combustion, industrial production, and motor vehicles.

Notably, O₃ was negatively correlated with CO (-0.723), NO₂ (-0.890), CH₄ (-0.387), and HCHO (-0.658). [Mahmud et al. \(2023\)](#) reported a negative correlation for O₃–NO₂ and O₃–CO. This indicates that the presence of higher concentrations of other air pollutants may affect O₃ either directly or indirectly. The relation observed among the pollutants is consistent with the results of [Zhao et al. \(2021\)](#).

Correlation Matrix of Climatic Variables

The correlation matrix of climatic variables shows positive, negative, strong, as well as weak correlations (Table 1). The correlation coefficient for Tmax – PRCP, Tmax - cloud cover, and PRCP - cloud cover are -0.741, -0.721, and 0.971 at $p < 0.01$. For Tmin – PRCP and Tmin - cloud cover are 0.503 and 0.504 at $p < 0.05$. For Tmax – Tmin, Tmax - wind speed, Tmin - wind speed, wind speed - PRCP, and wind speed - cloud cover are 0.179, 0.426, 0.155, -0.310, and -0.160 respectively. Among the climatic parameters considered, it could be observed that wind speed, Tmax, and Tmin tend to correlate with each other as compared to PRCP and cloud cover (which are strongly correlated).

Correlation Matrix of Air Pollutants and Climatic Variables

From the correlation matrix of air pollutants and climatic variables (Table 1), the correlation coefficient observed for CO - Tmax, CO - wind speed, and CO - PRCP are 0.800, 0.772, and -0.736 at $p < 0.01$, for CO - cloud cover was -0.595 at $p < 0.05$ and CO - Tmin was -0.041 respectively. Similarly, the correlation coefficient obtained for NO₂ – Tmax and NO₂ - wind speed are 0.606 and 0.632 at $p < 0.05$, NO₂ - PRCP and NO₂ - cloud cover are -0.830 and -0.773 at $p < 0.01$, and NO₂ – Tmin was -0.463. The correlation coefficient for CH₄ - Tmax was 0.716 at $p < 0.01$, while CH₄ – Tmin, CH₄ - wind speed, CH₄ – PRCP, and CH₄ - cloud cover are 0.165, -0.143, -0.460, and -0.463 respectively.

For O₃ - Tmax and O₃ - Tmin are -0.629 and 0.634 at $p < 0.05$, O₃ - PRCP and O₃ - cloud cover are 0.952 and 0.911 at $p < 0.01$, while O₃ - wind speed was -0.331. For HCHO - Tmax, HCHO – PRCP, and HCHO - cloud cover are 0.964, -0.726, and -0.687 respectively at $p < 0.01$, HCHO - wind speed was 0.575 at $p < 0.05$, and HCHO – Tmin was 0.147. This implies that correlations exist between air pollutants and climatic variables at varying strengths and directions. Using TROPOMI data, [Crosman \(2021\)](#) reported the influence of meteorological drivers on the variation of CH₄ in the Permian Basin. The relationship observed between HCHO - Tmax and HCHO - wind speed is consistent with [Li et al. \(2025\)](#) who noted that HCHO was strongly correlated with temperature and wind speed over North China. For HCHO – PRCP, we observed a strong but negative correlation in contrast to the weak correlation reported by [Li et al. \(2025\)](#).

Generally, our observation shows that in the correlation of air pollutants with climatic parameters, the significance of the correlation may vary based on the emission sources, concentration of pollutants, and atmospheric condition and stability of the study area. We hereby recommend industrial emission controls in November–March when pollutant concentrations peak. Also, real-time air quality alerts during high-temperature/low-wind episodes should be put in place due to their influence on pollutant dispersion. This will help to reduce exposure to air pollutants and the associated health impacts. The impacts of exposure to air pollutants observed could be short-term or long-term, resulting in respiratory challenges and complications in the lungs and heart. Short-term impacts include wheezing, chest constriction, coughing, nausea, headaches, and others. In contrast, long-term impacts include asthma, pneumonia, bronchitis, and possibly death ([Gul & Das, 2023](#)).

Temporal Trends of Air Pollutants from 2018 to 2023

The variation trend of yearly mean air pollutant concentrations over Nigeria from 2018 to 2023 is presented in Figure 4. A notable observation is that all the pollutants varied from year to year. Generally, increasing trends were observed for the period under study. The observed increasing trend in the pollutants is consistent with the global warming trend. This may be due to the fact that most of the pollutants are greenhouse gases, which are the major contributors to global warming. Another notable observation is the reduction in pollutant concentrations during the COVID-19 lockdown in 2020, as mentioned earlier. The decrease was larger for NO₂ than for the other pollutants (Figure 4). This suggests that the reductions in pollutants reported earlier during the lockdown varied from one pollutant to another.

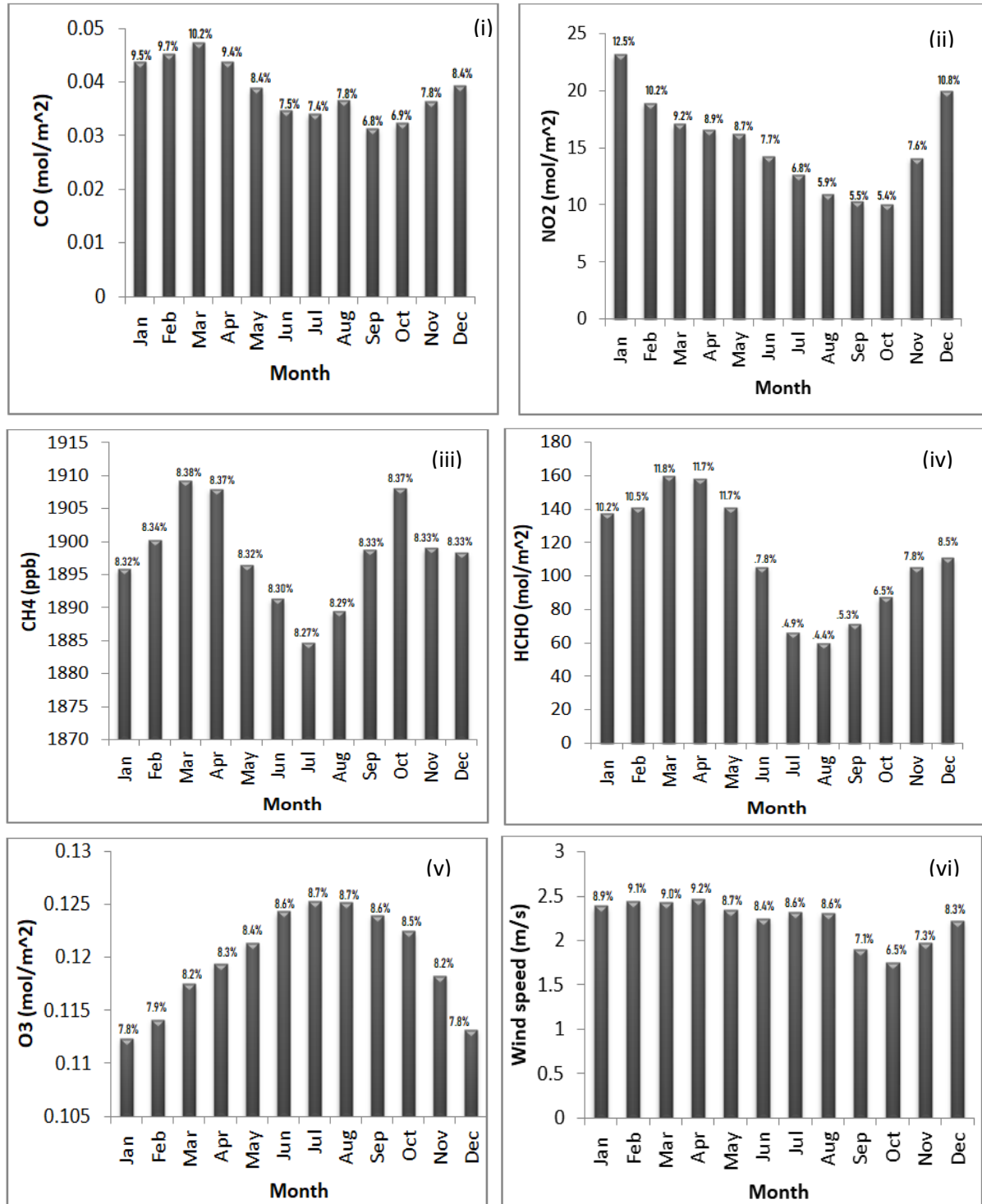


Figure 1. Monthly mean daily variation of (i) CO (ii) NO₂ (iii) CH₄ (iv) HCHO (v) O₃ and (vi) wind speed (2018–2023).

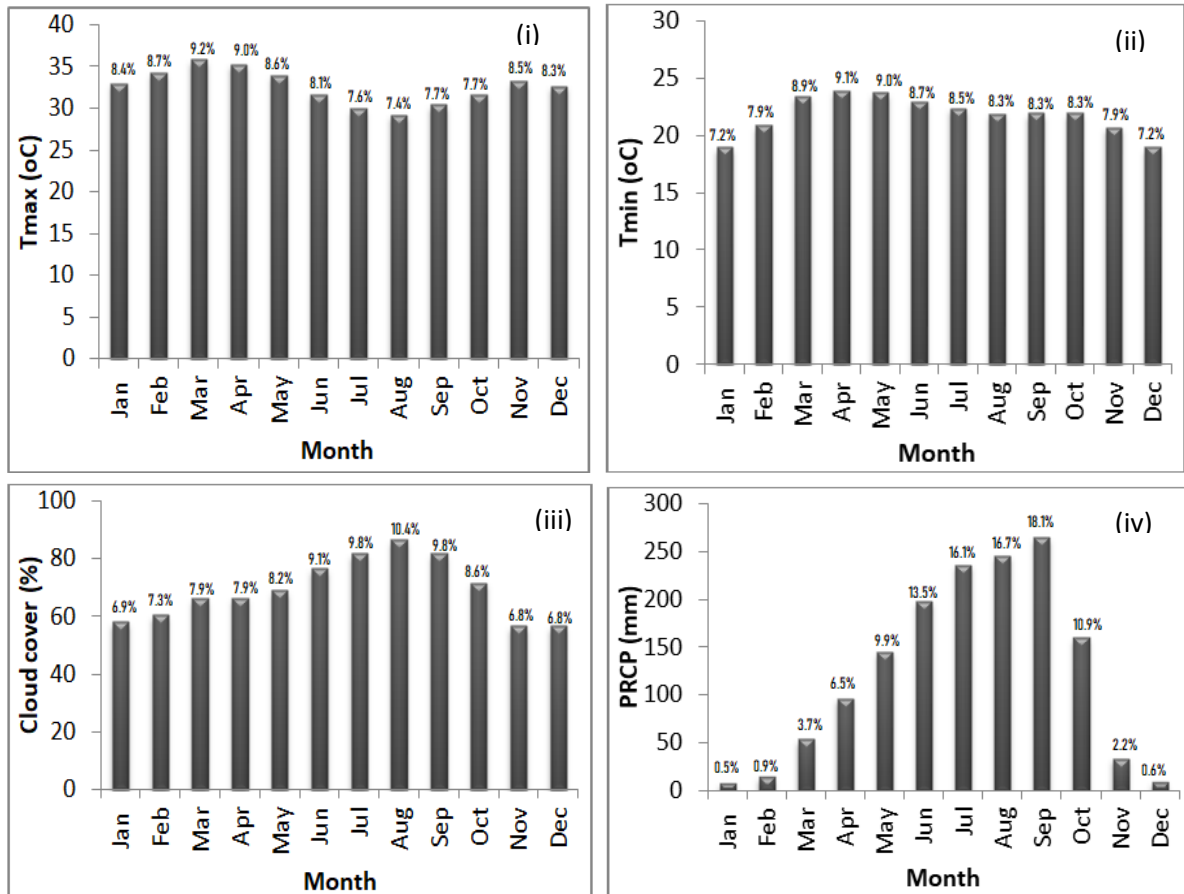


Figure 2. Monthly mean daily variation of (i) Tmax (ii) Tmin (iii) cloud cover, and (iv) PRCP (2018–2023).

Table 1. Pearson correlation matrix of air pollutants and climatic variables

Pollutants and variables	CO	NO ₂	CH ₄	O ₃	HCHO	Tmax	Tmin	Wind speed	PRCP	Cloud cover
CO	1.000									
NO ₂	0.783**	1.000								
CH ₄	0.419	0.135	1.000							
O ₃	-0.723**	-0.890**	-0.387	1.000						
HCHO	0.860**	0.728**	0.600*	-0.658*	1.000					
Tmax	0.800**	0.606*	0.716**	-0.629*	0.964**	1.000				
Tmin	-0.041	-0.463	0.165	0.634*	0.147	0.179	1.000			
Wind speed	0.772**	0.632*	-0.143	-0.331	0.575*	0.426	0.155	1.000		
PRCP	-0.736**	-0.830**	-0.460	0.952**	-0.726**	-0.741**	0.503*	-0.310	1.000	
Cloud cover	-0.595*	-0.773**	-0.463	0.911**	-0.687**	-0.721**	0.504*	-0.160	0.971**	1.000

** . Correlation is significant at the 0.01 level (1-tailed)

* . Correlation is significant at the 0.05 level (1-tailed)

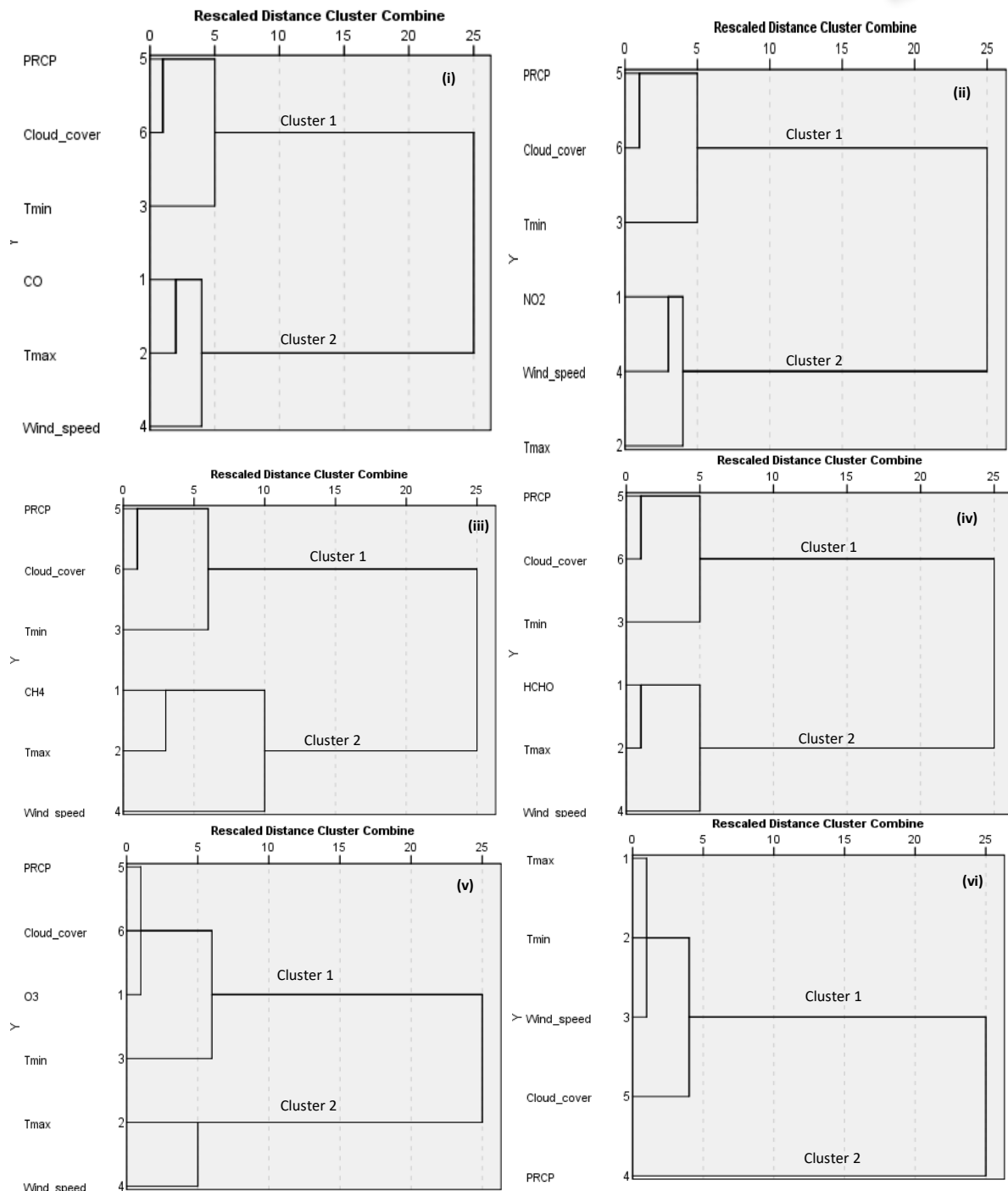


Figure 3. Dendrogram cluster of air pollutants and climatic variables using Ward Linkage method.

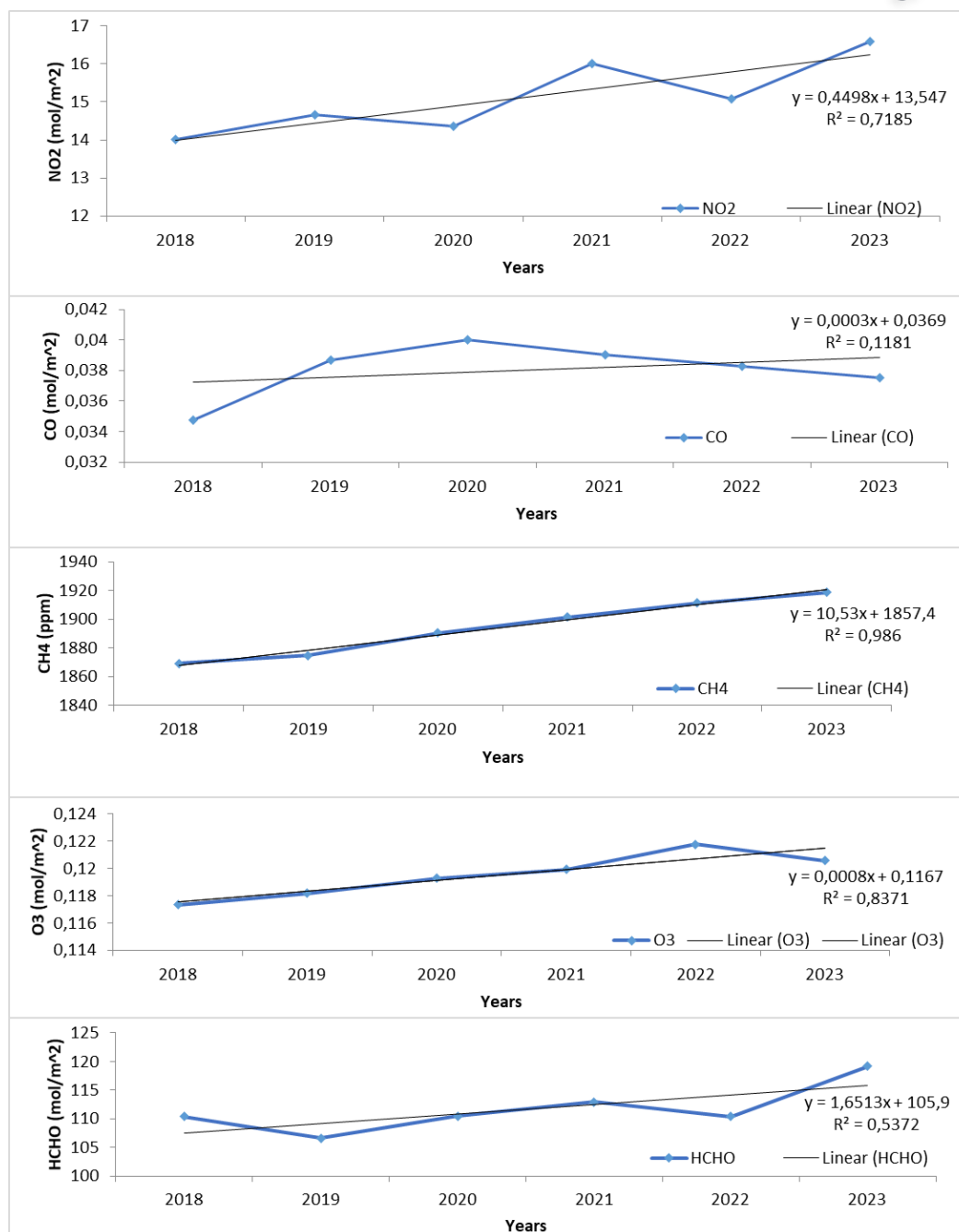


Figure 4. Variation trend of yearly mean air pollutant concentrations over Nigeria (2018–2023).

CONCLUSION

The following conclusions were drawn from this study. Tropospheric air pollutants and climatic parameters varied seasonally from one month to another. Similar variation patterns were observed among the pollutants except O₃; however, their concentrations differed from one month to another. Tropospheric O₃ has a unique variation pattern that differs entirely from those of the other pollutants. Our observations suggest that PRCP, cloud cover, and T_{min} could have more influence on O₃ than T_{max} and wind speed. Significant relationships were observed among some pollutants, among some climatic variables, and between climatic parameters and pollutants, consistent with earlier findings; however, the significance of the correlation varied based on the pollutants and the variables considered. Therefore, the influence of climatic parameters on pollutants varies from one study area to another. This may be attributed to emission sources, concentration of pollutants, and atmospheric condition and stability of the study area. This study provides a national-scale overview of tropospheric gaseous pollutants in Nigeria from November 2018 to December 2023. We suggest further studies of each vegetation zone of Nigeria and possibly each meteorological station in each region for more insight. Further studies on the

effects of factors such as natural events, extreme climate events, and anthropogenic activities on the seasonal distribution of tropospheric air pollutants are also recommended.

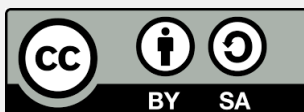
ACKNOWLEDGMENT

The authors thank the University of East Anglia (Norwich, United Kingdom) and the Copernicus Data Space Ecosystem for providing the meteorological parameters and air pollutants data. The authors appreciate the anonymous reviewers for their valuable comments and suggestions that significantly improved the clarity, coherence, and overall quality of the manuscript.

REFERENCES

- Abulude, F. O., Akinnusotu, A., Bello, L., & Feyisetan, A. O. (2022). Assessment of AQI, PM₁₀, PM_{2.5}, NO₂, O₃: The case of Owo, Nigeria. *ASEAN Journal of Science and Engineering*, 4(1), 15–24. <https://doi.org/10.17509/ajse.v4i1.51433>
- Adeyemi, A. J., Kanee, R. B., Edokpa, D. O., & Ede, P. N. (2021). Short-term air quality gains of COVID-19 pandemic lockdown of Port Harcourt, Nigeria. *Journal of Geoscience and Environment Protection*, 9(2), 110–123. <https://doi.org/10.4236/gep.2021.92007>
- Agarwal, R., Jayaraman, G., Anand, S., & Marimuthu, P. (2006). Assessing respiratory morbidity through pollution status and meteorological conditions for Delhi. *Environmental Monitoring and Assessment*, 114(1–3), 489–504. <https://doi.org/10.1007/s10661-006-4935-3>
- Ahmadi, H., Ahmadi, T., Shahmoradi, B., Mohammadi, S., & Kohzadi, S. (2015). The effect of climatic parameters on air pollution in Sanandaj, Iran. *Journal of Advances in Environmental Health Research*, 3(1), 49–61. <https://doi.org/10.22102/jaehr.2015.40185>
- Akinfolarin, O. M., Obunwo, C. C., & Boisa, N. (2018). Air quality characteristics of emerging industrial areas in Port Harcourt, Nigeria. *Journal of the Chemical Society of Nigeria*, 43(1), 7–14.
- Alonso, C., Gouveia, C. M., & Santos, J. A. (2025). Analysis of tropospheric ozone concentration and their predictors in mainland Portugal. *Atmospheric Research*, 314, 107766. <https://doi.org/10.1016/j.atmosres.2024.107766>
- Amanabo, H., & Umaru, B. S. (2022). Ambient air quality assessment for three criteria air pollutants (NO₂, SO₂, and PM₁₀) under various land uses in Gwagwalada, FCT. *Science World Journal*, 17(3), 361–367.
- Anderson, H. R. (2009). Air pollution and mortality: A history. *Atmospheric Environment*, 43(1), 142–152. <https://doi.org/10.1016/j.atmosenv.2008.09.026>
- Atubi, A., & Osoyibo, J. (2020). Spatial distribution and levels of air quality parameters within Asaba and environs, Delta State, Nigeria. *PARIPEX Indian Journal of Research*, 9(2), 63–68. <https://doi.org/10.36106/paripex/7812316>
- Beamish, L. A., Osornio-Vargas, A. R., & Wine, E. (2011). Air pollution: An environmental factor contributing to intestinal disease. *Journal of Crohn's and Colitis*, 5(4), 279–286. <https://doi.org/10.1016/j.crohns.2011.02.017>
- Bobak, M. (2000). Outdoor air pollution, low birth weight, and prematurity. *Environmental Health Perspectives*, 108(2), 173–176. <https://doi.org/10.1289/ehp.00108173>
- Chukwu, T. M., Morse, S., & Murphy, R. J. (2022). Spatial analysis of air quality assessment in two cities in Nigeria: A comparison of perceptions with instrument-based methods. *Sustainability*, 14(9), Article 5403. <https://doi.org/10.3390/su14095403>
- Crosman, E. (2021). Meteorological drivers of Permian Basin methane anomalies derived from TROPOMI. *Remote Sensing*, 13(5), Article 896. <https://doi.org/10.3390/rs13050896>
- Curtis, L., Rea, W., Smith-Willis, P., Fenyves, E., & Pan, Y. (2006). Adverse health effects of outdoor air pollutants. *Environment International*, 32(6), 815–830. <https://doi.org/10.1016/j.envint.2006.03.012>
- Daful, M. G., Adewuyi, T. O., Muhammad, M. N., Oluwole, O. A., Dadan-Garba, A., & Ezeamaka, C. K. (2020). Assessment of the spatial relationship between air pollutants in Kaduna metropolis, Nigeria. *Journal of Sustainable Development*, 13(4), 204–222. <https://doi.org/10.5539/jsd.v13n4p204>
- Datti, A. D., Zeng, G., Tarnavsky, E., Cornforth, R., Pappenberger, F., Abdullahi, B. A., & Onyejuruwa, A. (2024). Evaluation of satellite-based rainfall estimates against rain gauge observations across agro-climatic zones of Nigeria, West Africa. *Remote Sensing*, 16(10), Article 1755. <https://doi.org/10.3390/rs16101755>
- Gul, H., & Das, B. K. (2023). The impacts of air pollution on human health and well-being: A comprehensive review. *Journal of Environmental Impact and Management Policy*, 3(6), 1–11. <https://doi.org/10.55529/jeimp.36.1.11>
- Li, L., Ma, X., & Chen, D. (2025). Spatiotemporal evolution characteristics and drivers of TROPOMI-based tropospheric HCHO column concentration in North China. *Sustainability*, 17(10), Article 4386. <https://doi.org/10.3390/su17104386>
- Likens, G. E. (2021). Ambio's legacy on monitoring, impact, analysis and management of acid rain. *Ambio*, 50(2), 278–280. <https://doi.org/10.1007/s13280-020-01409-6>
- Mahmud, K., Mitra, B., Uddin, M. S., Hridoy, A. E., Aina, Y. A., Abubakar, I. R., Rahman, S. M., Tan, M. L., & Rahman, M. M. (2023). Temporal assessment of air quality in major cities in Nigeria using satellite data. *Atmospheric Environment: X*, 20, Article 100227. <https://doi.org/10.1016/j.aeaoa.2023.100227>
- Mills, G., Pleijel, H., Malley, C. S., Sinha, B., Cooper, O. R., Schultz, M. G., Neufeld, H. S., Simpson, D., Sharps, K., Feng, Z., Gerosa, G., Harmens, H., Kobayashi, K., Saxena, P., Paoletti, E., Sinha, V., & Xu, X. (2018).

- Tropospheric Ozone Assessment Report: Present-day tropospheric ozone distribution and trends relevant to vegetation. *Elementa: Science of the Anthropocene*, 6, Article 47. <https://doi.org/10.1525/elementa.302>
- Odediran, E. T., Yusuf, R. O., & Adeniran, J. A. (2022). Impacts of COVID-19 lockdown on concentration levels of traffic-related air pollutants in Ibadan—A West African city. *Nigerian Journal of Technological Development*, 19(3), 206–222. <https://doi.org/10.4314/njtd.v19i3.3>
- Okimiji, O. P., Techato, K., Simon, J. N., Tope-Ajayi, O. O., Okafor, A. T., Aborisade, M. A., & Phoungthong, K. (2021). Spatial pattern of air pollutant concentrations and their relationship with meteorological parameters in coastal slum settlements of Lagos, southwestern Nigeria. *Atmosphere*, 12(11), Article 1426. <https://doi.org/10.3390/atmos12111426>
- Okoro, P. D., Frayssinet, A., De Oliveira, S., Rouquier, L., Miklosic, G., d'Este, M., Potier, E., & H  lary, C. (2023). Combining biomimetic collagen/hyaluronan hydrogels with discogenic growth factors promotes mesenchymal stroma cell differentiation into Nucleus Pulposus like cells. *Biomaterials Science*, 11(24), 7768–7783. <https://doi.org/10.1039/d3bm01025b>
- Olatunde, V., & Ajayi, I. (2020, November 10–11). *Air quality assessment during COVID-19 lockdown in Ilaro, Ogun State, Nigeria* [Paper presentation], 2nd International Conference, The Federal Polytechnic, Ilaro, Nigeria.
- Olomiyesan, B. M., & Oyedum, O. D. (2016). Comparative study of ground measured, satellite-derived, and estimated global solar radiation data in Nigeria. *Journal of Solar Energy*, 2016, Article 8197389. <https://doi.org/10.1155/2016/8197389>
- Omoko, E. N., Onyekuru, S. O., Opara, A. I., Usen, O. S., Ukpong, A. J., & Adikwu, S. O. (2021). Air quality assessment in parts of Onne, Rivers State, Southeastern Nigeria. *Journal of Physical Representation*, 6(1), 23–24.
- Omokpariola, D. O., Nduka, J. N., & Omokpariola, P. L. (2024). Short-term trends of air quality and pollutant concentrations in Nigeria from 2018–2022 using tropospheric Sentinel-5P and 3A/B satellite data. *Discover Applied Sciences*, 6(4), Article 182. <https://doi.org/10.1007/s42452-024-05856-8>
- Onwosi, I. I., & Nymphas, E. F. (2022). Impact of concentration levels of atmospheric pollutants on local climate of Delta State, Nigeria. *Atmospheric and Climate Sciences*, 12(2), 421–440. <https://doi.org/10.4236/acs.2022.122025>
- Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., Rodriguez, J. D.D., & Calatayud, V. (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *Science of the total environment*, 735, 139542. <https://doi.org/10.1016/j.scitotenv.2020.139542>
- Veefkind, J. P., Aben, I., McMullan, K., F  rster, H., De Vries, J., Otter, G., ... & Levelt, P. F. (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GME mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote sensing of environment*, 120, 70–83. <https://doi.org/10.1016/j.rse.2011.09.027>
- Vincent, E. W., Sadiq, I., Jimmy, A., & Temi, E. O. (2017). On the relationship between atmospheric pollutants and meteorological parameters along major traffic corridors in Port Harcourt metropolis, Nigeria. *International Journal of Environment and Pollution Research*, 5(2), 15–25.
- Zhao, C., Sun, Y., Zhong, Y., Xu, S., Liang, Y., Liu, S., He, X., Zhu, J., Shibamoto, T., & He, M. (2021). Spatio-temporal analysis of urban air pollutants throughout China during 2014–2019. *Air Quality, Atmosphere & Health*, 14(10), 1619–1632. <https://doi.org/10.1007/s11869-021-01043-5>



Copyright (c) 2025 by the authors. This work is licensed under a [Creative Commons Attribution-ShareAlike 4.0 International License](https://creativecommons.org/licenses/by-sa/4.0/).