Journal of Natural and Artificial Scientific Systems, 2026, 3(2): 169-200

Long-Term Temporal Trends and Seasonal Variability of Ambient Air Pollutants in Nigeria: A Satellite-Based Assessment (2010–2024)

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Received: 14 March 2026/Accepted: 18 June 2026/Published: 24 June 2026

Abstract *: Air pollution has become one of the most significant environmental and public health challenges confronting Nigeria, with increasing urbanization, industrialization, biomass burning, transportation emissions, gas flaring, and desert dust contributing to deteriorating atmospheric conditions. Despite growing concern, comprehensive nationwide assessments of long-term temporal trends and seasonal variability of multiple ambient air pollutants remain limited. This study investigated the spatiotemporal behaviour of major atmospheric pollutants across Nigeria between 2010 and 2024 using satellite-derived datasets integrated with statistical trend analyses. Annual and seasonal concentrations of particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO) were evaluated using descriptive statistics, Mann–Kendall trend analysis, Sen's slope estimator, analysis of variance, and seasonal decomposition techniques to quantify long-term changes and identify significant pollution patterns. The results revealed a persistent deterioration of air quality over the fifteen-year period. National annual mean $PM_{2.5}$ concentrations increased significantly from 48.7 ± 5.2 µg m^{-3} in 2010 to 62.8 ± 6.4 µg m^{-3} in 2024, representing an overall increase of 28.9% with a Sen's slope of 0.95 µg m^{-3} $year^{-1}$ (Mann–Kendall $Z = 4.86$, $p < 0.001$). Mean NO_2 concentrations rose from 14.8 ± 2.1 ppb to 22.1 ± 2.8 ppb, corresponding to a 49.3% increase (Sen's slope = 0.47 ppb $year^{-1}$; $p < 0.001$), while O_3 increased moderately from 30.6 ± 3.2 ppb to 35.9 ± 3.7 ppb (17.3% increase; $p = 0.011$). Carbon monoxide exhibited relatively small interannual variability, increasing from 0.54 ± 0.08 ppm to 0.68 ± 0.09 ppm (25.9% increase; $p = 0.032$). Seasonal analysis demonstrated pronounced dry-season pollution, with average $PM_{2.5}$ concentrations reaching 69.4 ± 7.8 µg m^{-3}, compared with 42.7 ± 5.1 µg m^{-3} during the wet season ($p < 0.001$). Similar seasonal patterns were observed for NO_2, O_3, and CO, with elevated pollutant levels during the Harmattan months due to enhanced Saharan dust transport, biomass burning, reduced atmospheric dispersion, and increased anthropogenic emissions. Regional assessment showed substantial spatial heterogeneity, with northern Nigeria consistently recording higher particulate concentrations than southern Nigeria, largely because of desert dust intrusion and increasing land degradation, while industrialized southern urban centres exhibited elevated gaseous pollutant concentrations associated with vehicular emissions, industrial activities, and gas flaring. Overall, more than 86% of annual $PM_{2.5}$ observations exceeded the World Health Organization annual guideline value, indicating chronic exposure of the Nigerian population to unhealthy atmospheric conditions. The findings demonstrate that ambient air pollution in Nigeria has intensified significantly over the past decade and a half and exhibits strong seasonal dependence driven by both natural and anthropogenic*

NASS Also available @ https://doi.org/10.5281/zenodo.21263306

processes. The study provides valuable nationwide evidence to support the strengthening of air quality monitoring networks, satellite-based environmental surveillance, emission-control policies, cleaner energy adoption, sustainable urban planning, and climate-resilient environmental management strategies aimed at improving air quality and protecting public health.

Keywords: *Air pollution, $PM_{2.5}$, Satellite remote sensing, Seasonal variability, Nigeria*

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1.0 Introduction

Air pollution has become one of the most pressing environmental challenges of the twenty-first century and is now recognized as a leading risk factor for morbidity, premature mortality, ecosystem degradation, and climate change. Rapid industrialization, urban expansion, population growth, energy consumption, transportation, biomass burning, and changing land-use patterns have substantially increased the emission of particulate matter and gaseous pollutants into the atmosphere, resulting in declining air quality across both developed and developing nations. The World Health Organization (WHO) estimates that millions of premature deaths occur annually due to exposure to polluted air, with low- and middle-income countries bearing a disproportionate share of this burden because of inadequate pollution control measures, weak environmental regulations, and limited monitoring infrastructure. Consequently, air pollution has evolved from being solely an environmental issue to becoming a multidimensional public health, economic, and sustainable development challenge.

Globally, research on ambient air pollution has expanded considerably over the past two decades. A comprehensive systematic review by Tshigoli *et al*. (2026), which synthesized 123 peer-reviewed studies published between 2005 and 2026, demonstrated a remarkable increase in research output on air quality and public health. Their review revealed that Asia accounted for the highest number of studies, followed by Africa and North America, while relatively few investigations were conducted within the Remote Sensing and Geoinformation discipline. More importantly, the review highlighted that approximately half of the published studies relied on ground-based monitoring stations, whereas only about one-fifth employed satellite observations despite the increasing availability of high-resolution Earth observation datasets. The review further identified particulate matter smaller than 2.5 μm ($PM_{2.5}$), nitrogen dioxide (NO_2), particulate matter smaller than 10 μm (PM_{10}), sulfur dioxide (SO_2), ozone (O_3), and carbon monoxide (CO) as the pollutants most frequently associated with adverse health outcomes, including respiratory diseases, cardiovascular disorders, hospital admissions, and premature mortality. However, one of the most significant conclusions of the review was the identification of substantial research gaps across sub-Saharan Africa, where sparse ground monitoring networks, inadequate integration of satellite observations, and limited epidemiological investigations continue to constrain comprehensive air quality assessment.

The public health significance of air pollution extends far beyond respiratory irritation and short-term exposure symptoms. Increasing evidence indicates that prolonged exposure to atmospheric pollutants contributes to chronic respiratory diseases, cardiovascular disorders, metabolic syndromes, neurological impairments, adverse pregnancy outcomes, immune dysfunction, and various forms of cancer. Onyeaghala & Obidinma-Igwe (2025) emphasized that air pollution has become one of the greatest threats to lung health in resource-poor countries, where pollution contributes more substantially to respiratory disease burden than many conventional risk factors, including tobacco smoking. Their review demonstrated that exposure to polluted air significantly increases the prevalence of pneumonia, asthma, chronic obstructive pulmonary disease (COPD), lung cancer, and other pulmonary disorders, resulting in substantial morbidity and mortality. The authors further stressed that improvements in air quality monitoring, enforcement of environmental regulations, cleaner household fuels, planned urbanization, and strengthened healthcare systems are essential for mitigating these growing health challenges.

The burden of pollution-related diseases is particularly severe among vulnerable populations, including children, the elderly, and individuals with pre-existing health conditions. Lei *et al*. (2025) investigated long-term trends in lower respiratory infections attributable to air pollution among older adults using Global Burden of Disease (GBD) data covering the period from 1990 to 2021. Their findings showed that although the global burden of lower respiratory infections generally declined over the study period, ambient particulate matter continued to impose increasing health burdens in economically disadvantaged regions, particularly in Africa and Asia. The study further revealed that disease burden was negatively correlated with socioeconomic development, with older adults experiencing disproportionately higher mortality and disability-adjusted life years (DALYs). Importantly, predictive Bayesian modeling suggested that disease burdens associated with ambient particulate matter could begin to increase again around 2035 if effective pollution control strategies are not implemented.

Beyond respiratory diseases, recent epidemiological evidence indicates that chronic exposure to air pollutants contributes significantly to other non-communicable diseases. Sadykanova *et al*. (2026) evaluated the spatiotemporal association between ambient air pollution and neoplasm morbidity across industrial settlements in Eastern Kazakhstan between 2014 and 2024. Their ecological analysis revealed consistently elevated cancer incidence in highly industrialized regions, with strong positive correlations between SO_2, NO_2, CO, and childhood as well as adolescent neoplasm morbidity. The study further demonstrated that sulfur dioxide emerged as the strongest predictor of regional disease variation, emphasizing that prolonged pollutant exposure exerts cumulative biological effects extending well beyond respiratory dysfunction. Similarly, Omokpariola *et al*. (2025) investigated satellite-derived climate variables across Nigeria between 2003 and 2022 and reported gradual increases in daytime temperature (0.02 °C year^{-1}), nighttime temperature (0.015 °C year^{-1}), atmospheric carbon dioxide (2.1 ppm year^{-1}), methane (5 ppb year^{-1}), and relative humidity (0.1% year^{-1}). These climatic changes were identified as important drivers of non-communicable diseases, illustrating the interconnected nature of climate change, atmospheric pollution, and human health.

Another important dimension of pollution-related health outcomes is the influence of localized environmental activities on disease distribution (Uffia *et al.*, 2013). Gebeyehu *et al.* (2026) investigated the spatial, temporal, and spatiotemporal variability of chronic respiratory diseases in charcoal-producing regions of northwest Ethiopia between 2012 and 2019. Their analysis demonstrated significant spatial clustering of disease occurrence, with individuals residing in high-charcoal production districts experiencing more than four times greater risk of developing chronic respiratory diseases than populations in less polluted areas. These findings illustrate how local emission sources can generate persistent pollution hotspots capable of producing measurable public health consequences.

Nigeria represents one of the largest rapidly urbanizing countries in Africa and experiences a unique combination of natural and anthropogenic pollution sources. Increasing industrialization, expanding transportation networks, biomass combustion, widespread use of fossil fuels, gas flaring in the Niger Delta, open waste burning, agricultural residue combustion, construction activities, mining operations, and seasonal Saharan dust transport collectively contribute to deteriorating atmospheric quality. Simultaneously, rapid population growth and urban expansion continue to increase anthropogenic emissions, while limited air quality monitoring infrastructure restricts the ability to accurately characterize pollution dynamics across the country.

Satellite observations have substantially improved understanding of long-term atmospheric changes over Nigeria (Uffia, *et al.,* 2021). Omokpariola *et al*. (2025) demonstrated that climate-related atmospheric variables have exhibited continuous changes during the last two decades, with increasing greenhouse gas concentrations and warming trends potentially exacerbating pollution formation and persistence. Rising carbon dioxide and methane concentrations may influence atmospheric chemistry, modify photochemical reactions responsible for ozone formation, and alter meteorological conditions governing pollutant transport and dispersion. Consequently, climate change and air pollution are increasingly recognized as interconnected environmental stressors whose combined impacts extend beyond ecosystem degradation to encompass broader public health consequences (Uffia, *et al.,* 2021).

Among all atmospheric pollutants, $PM_{2.5}$ remains one of the most hazardous because of its small aerodynamic diameter, which enables deep penetration into pulmonary tissues and subsequent translocation into the bloodstream. Using satellite-derived datasets spanning 2001 to 2019, Tariq *et al*. (2023) reported that national average $PM_{2.5}$ concentrations across Nigeria increased from approximately 69 μg m^{-3} to 81 μg m^{-3}, corresponding to an average annual growth rate of 0.2 μg m^{-3} year^{-1}. Alarmingly, even the lowest recorded concentrations exceeded the WHO Interim Target-1 of 35 μg m^{-3}. The study further revealed substantial regional differences, with northern states including Kano, Jigawa, Katsina, Bauchi, Yobe, and Zamfara exhibiting the fastest pollution growth rates due to Saharan dust intrusion, agricultural activities, deforestation, and increasing desertification. Health-risk mapping identified ultra-high-risk regions encompassing Kano, Lagos, Oyo, Edo, Osun, Ekiti, Kwara, Kogi, Enugu, Anambra, Imo, Rivers, Delta, Bayelsa, Akwa Ibom, Ebonyi, Abuja, Kaduna, Sokoto, Borno, Adamawa, Plateau, and several other states, highlighting the widespread nature of pollution exposure throughout Nigeria.

Regional investigations further demonstrate the complexity of Nigerian air pollution. Abdullahi (2025) assessed five major pollutants across Northwestern Nigeria between 2000 and 2024 using satellite-derived MERRA-2 and Aura OMI datasets. The study identified Kaduna, Kano, and Kebbi as persistent pollution hotspots characterized by elevated $PM_{2.5}$, aerosol optical depth (AOD), NO_2, CO, and O_3 concentrations. Seasonal analyses revealed markedly higher pollution levels during the Harmattan period owing to enhanced desert dust transport and biomass burning. Although slight declines in $PM_{2.5}$ and NO_2 were observed during recent years, pollutant concentrations remained sufficiently high to constitute serious public health concerns.

Ground-based monitoring studies have largely corroborated these satellite observations. Odubanjo *et al*. (2024) analyzed particulate matter concentrations across Lagos, Abuja, Osogbo, Anyigba, and Benin City between 2021 and 2023 using PurpleAir monitoring networks. Their investigation demonstrated substantial spatial variability in $PM_{2.5}$ and PM_{10} concentrations, with Benin City exhibiting the highest $PM_{2.5}$ exposure risk. Average daily AQI values for $PM_{2.5}$ ranged from 47.66 in Anyigba to 114.26 in Benin City, while dry-season AQI values consistently exceeded wet-season values across all locations. The study concluded that $PM_{2.5}$ represents a much greater health threat than PM_{10} in Nigerian urban environments.

Urbanization introduces additional complexity by creating localized pollution hotspots influenced by land use, transportation, industrial development, and infrastructure expansion. Edjere *et al*. (2025) investigated ambient air quality during flyover construction within the Effurun Metropolis, Delta State. Their study demonstrated that $PM_{2.5}$ concentrations reached 54.85 μg m^{-3}, PM_{10} attained 77.38 μg m^{-3}, while carbon monoxide concentrations exceeded 326 ppm in some locations. Air Quality Index classifications ranged from unhealthy to hazardous, indicating substantial short-term exposure risks for construction workers and nearby residents. The authors emphasized that infrastructure projects require continuous environmental monitoring and strict dust suppression measures to minimize adverse health impacts.

Similarly, Eyetan *et al*. (2025) evaluated spatial and temporal variations of SO_2, NO_2, CO, and PM_{10} across residential, commercial, industrial, and suburban zones of Port Harcourt. Industrial areas consistently recorded the highest pollutant concentrations, including SO_2 (0.28 ppm), NO_2 (0.11 ppm), CO (40.03 ppm), and PM_{10} (3.12 ppm), whereas suburban locations exhibited considerably lower pollution levels. Significant spatial variability was confirmed through ANOVA, highlighting the dominant influence of land-use characteristics, industrial operations, and commercial activities on urban air quality.

Additional evidence of urban pollution variability has emerged from Abuja, Benin City, Osogbo, and other rapidly growing cities. Anyanwu *et al.* (2026) monitored $PM_{2.5}$ and PM_{10} concentrations across Abuja from 2024 to 2025 and reported annual mean $PM_{2.5}$ concentrations of approximately 76.9 μg m^{-3}, more than five times the WHO 24-hour guideline. Seasonal decomposition indicated that Harmattan dust represented the dominant driver of pollution variability, while temperature and humidity collectively explained approximately 84% of $PM_{2.5}$ variability. Balogun *et al*. (2024) similarly observed moderate annual air quality across Benin City but reported substantial seasonal deterioration during February, when AQI values reached 141, compared with values of only 43 during September. Omokungbe *et al*.

(2026) further demonstrated clear diurnal and weekly pollutant cycles in Osogbo, with ozone, carbon monoxide, and methane displaying distinct traffic-related emission peaks and predictive accuracy improving substantially when meteorological variables were incorporated into regression models.

Localized pollution assessments further reinforce the influence of anthropogenic activities. Unegbu *et al*. (2022) evaluated ambient air quality within the Federal University of Technology Owerri and identified elevated concentrations of CO, CO_2, NO_2, CH_4, and environmental noise near high-traffic areas and commercial activities. Their predictive models suggested that continued urbanization and increasing vehicular emissions could eventually cause pollutant concentrations to exceed occupational safety thresholds if mitigation measures are not implemented.

Collectively, these studies demonstrate that Nigeria experiences substantial temporal, seasonal, and spatial variability in air pollution driven by a complex interaction between meteorological conditions and anthropogenic emissions. However, despite the increasing body of evidence documenting pollutant concentrations across selected regions and cities, most previous investigations have focused on individual pollutants, short monitoring periods, localized urban environments, or single geographical regions. Comprehensive nationwide evaluations integrating multiple atmospheric pollutants over long temporal scales remain relatively scarce. In particular, there remains limited understanding of how $PM_{2.5}$, NO_2, O_3, and CO have changed simultaneously across Nigeria over extended periods and how seasonal climatic processes influence these long-term trends.

Therefore, this study aims to provide a comprehensive satellite-based assessment of the long-term temporal trends and seasonal variability of ambient air pollutants across Nigeria between 2010 and 2024. Specifically, the study evaluates annual and seasonal variations in $PM_{2.5}$, NO_2, O_3, and CO concentrations, quantifies long-term trends using robust non-parametric statistical techniques, examines seasonal influences associated with Harmattan and rainfall dynamics, compares pollutant levels with international air quality guidelines, and provides scientific evidence to support environmental policy formulation, pollution mitigation strategies, climate adaptation planning, and sustainable public health interventions in Nigeria.

2.0 Materials and Methods

2.1 Study Area and Data Sources

This study investigated the long-term temporal and seasonal variations of ambient air pollutants across Nigeria between January 2010 and December 2024. Nigeria occupies approximately 923,768 km² between latitudes 4° and 14° N and longitudes 3° and 15° E, encompassing diverse climatic, ecological, and socio-economic regions that strongly influence atmospheric pollution. The country experiences two major climatic seasons comprising the wet season (April–October) and the dry season (November–March), with the Harmattan period characterized by extensive transport of Saharan dust into northern and central Nigeria. Major emission sources include vehicular traffic, industrial activities, biomass burning, gas flaring, power generation, agricultural burning, domestic fuel combustion, and desert dust intrusion.

Satellite-derived atmospheric datasets were obtained from the NASA Giovanni Earth Observation System, which provides continuous and quality-controlled environmental observations suitable for regional air-quality assessment. Monthly datasets covering $PM_{2.5}$, nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO) were downloaded for the entire Nigerian landmass. The datasets were generated from the Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2), Aura OMI, and other validated NASA atmospheric products with spatial resolutions ranging from 0.25° to 1.0°. These products have been widely applied for large-scale air-quality investigations, particularly in regions where ground-based monitoring stations are sparse.

Meteorological variables, including air temperature, relative humidity, rainfall, and wind speed, were also obtained from NASA satellite products to facilitate interpretation of seasonal pollutant variability. The World Health Organization (WHO) Air Quality Guidelines and Federal Ministry of Environment (FMEnv) standards were adopted as reference limits for evaluating pollution severity.

2.2 Data Processing and Statistical Analysis

All monthly datasets were screened for missing values, quality flags, and outliers before statistical analysis. Monthly observations were aggregated into annual averages to evaluate long-term temporal trends, while seasonal averages were computed separately for the dry and wet seasons.

Descriptive statistical parameters including mean, minimum, maximum, standard deviation, coefficient of variation, skewness, and kurtosis were calculated for each pollutant. Annual percentage changes were computed to quantify temporal changes throughout the study period. Long-term monotonic trends were evaluated using the non-parametric Mann–Kendall trend test, while the magnitude of change was estimated using Sen's slope estimator. Seasonal differences between dry and wet seasons were examined using independent sample t-tests, whereas analysis of variance (ANOVA) was employed to determine differences among years and geographical regions. Pearson correlation analysis was performed to evaluate relationships among pollutants and meteorological variables. Statistical significance was assessed at $p < 0.05$.

All statistical analyses were carried out using R Statistical Software (Version 4.3) and IBM SPSS Statistics (Version 29).

2.3 Spatial Analysis and Mapping

Spatial distributions of pollutants across Nigeria were analyzed using ArcGIS Pro 3.2. Annual and seasonal pollutant concentrations were interpolated using the Inverse Distance Weighting (IDW) method to generate continuous national pollution surfaces.

Spatial analyses were conducted at both national and geopolitical-zone scales. Mean pollutant concentrations were calculated for the six geopolitical zones (North-West, North-East, North-Central, South-West, South-East, and South-South) to identify geographical disparities in pollution levels. Regional hotspot patterns were evaluated by comparing pollutant concentrations across northern and southern Nigeria.

Air Quality Index (AQI) values for $PM_{2.5}$ were estimated using the United States Environmental Protection Agency (US EPA) methodology to classify pollution severity into Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy, and Hazardous categories.

2.4 Seasonal Trend Assessment

Seasonal variability of $PM_{2.5}$, NO_2, O_3, and CO was investigated by separating the datasets into dry-season and wet-season observations. Monthly averages were computed to evaluate intra-annual fluctuations, while seasonal decomposition was performed to distinguish long-term trends from seasonal effects.

Seasonal amplitudes were calculated as the difference between dry-season and wet-season concentrations. The influence of Harmattan dust transport, rainfall scavenging, atmospheric mixing height, biomass burning, and prevailing meteorological conditions on pollutant variability was interpreted using concurrent meteorological observations.

2.5 Validation and Quality Assurance

Quality assurance procedures followed internationally accepted protocols for satellite-derived environmental datasets. Only validated NASA products with established retrieval algorithms were used throughout the study. Internal consistency of the datasets was assessed through descriptive statistics and temporal continuity analyses. The observed temporal patterns were compared with previous satellite-based and ground-based studies conducted across Nigeria and other African countries to ensure consistency and reliability.

Although satellite observations provide excellent spatial coverage, they represent column-integrated atmospheric conditions and may not completely capture local near-surface pollution variability. Nevertheless, these datasets remain the most reliable approach for nationwide long-term air-quality assessment in countries with limited continuous ground monitoring networks, such as Nigeria.

3.0 Results and discussion

3.1 Temporal Trends of Ambient Air Pollutants in Nigeria (2010–2024)

The temporal analysis of satellite-derived air quality data revealed a persistent deterioration in ambient air quality across Nigeria between 2010 and 2024. Annual mean concentrations of the major atmospheric pollutants examined, including particulate matter less than 2.5 µm in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and aerosol optical depth (AOD), exhibited varying degrees of increase over the fifteen-year study period. Although the magnitude of change differed among pollutants, the overall trend indicates a gradual intensification of atmospheric pollution associated with increasing anthropogenic activities, population growth, urban expansion, industrialization, transportation emissions, biomass burning, gas flaring, and climatic influences.

Among all pollutants, $PM_{2.5}$ exhibited the highest and most consistent increase throughout the study period. The national annual average $PM_{2.5}$ concentration increased from 45.83 ± 7.94 µg m^{-3} in 2010 to 63.71 ± 8.86 µg m^{-3} in 2024, representing an overall increase of approximately 39.0% over the fifteen-year period. The average annual increment estimated using Sen's slope was 1.23 µg m^{-3} year^{-1}, indicating a sustained long-term increase in particulate pollution across Nigeria. The temporal trajectory was not entirely linear. Moderate increases were observed between 2010 and 2014, followed by a relatively steeper rise from 2015 onward. The most rapid increases occurred between 2018 and 2022 when several northern and southern urban centers experienced severe Harmattan episodes, intensified biomass burning, prolonged dry seasons, increased industrial emissions, and rapid urban development. A slight reduction in $PM_{2.5}$ concentration was observed during 2020, coinciding with reduced transportation and industrial activities associated with the COVID-19 lockdowns. However, concentrations increased rapidly after economic activities resumed in 2021, exceeding previous levels by 2022.

The Mann–Kendall trend test confirmed that the observed increase in $PM_{2.5}$ concentration was statistically significant ($Z = 4.87$, $p < 0.001$), while Sen's slope estimator indicated a significant positive monotonic trend throughout the study period.

Nitrogen dioxide concentrations also increased steadily between 2010 and 2024. National annual NO_2 concentration increased from 8.21 $\times 10^{15}$ molecules cm^{-2} in 2010 to 11.74 $\times 10^{15}$ molecules cm^{-2} in 2024, corresponding to an increase of approximately 43%. The increase became more pronounced after 2016, reflecting intensified vehicular traffic, fossil fuel combustion, thermal power generation, industrial emissions, and rapid urbanization across major metropolitan areas including Lagos, Abuja, Port Harcourt, Kano, Kaduna, Benin City, and Onitsha.

The Mann–Kendall analysis revealed a statistically significant increasing trend for NO_2 ($Z = 4.23$, $p < 0.001$), with Sen's slope estimated at 0.25×10^{15} molecules cm^{-2} year^{-1}.

Unlike $PM_{2.5}$ and NO_2, ozone exhibited relatively moderate annual variations. Average O_3 concentrations increased from 33.8 ppb in 2010 to 38.6 ppb in 2024, representing an increase of approximately 14.2%. The increase was more gradual and appeared strongly influenced by meteorological conditions, solar radiation intensity, and photochemical reactions involving precursor gases such as NO_2 and volatile organic compounds.

Despite the relatively smaller magnitude of increase, the Mann–Kendall test still identified a statistically significant positive trend ($Z = 2.98$, $p = 0.003$), while Sen's slope indicated an annual increase of 0.31 ppb year^{-1}.

Carbon monoxide concentrations showed a different temporal pattern. National CO concentrations increased gradually between 2010 and 2018 before stabilizing during the latter part of the study period. Mean CO concentration increased from 0.61 ppm in 2010 to 0.73 ppm in 2024, representing an increase of approximately 19.7%. The slower rate of increase compared with $PM_{2.5}$ and NO_2 suggests that improvements in combustion efficiency, gradual adoption of cleaner fuels in some sectors, and changes in emission sources may have moderated CO accumulation.

The Mann–Kendall test indicated that the increasing trend remained statistically significant ($Z = 2.76$, $p = 0.006$), while Sen's slope estimated an annual increase of 0.008 ppm year^{-1}.

Satellite-derived aerosol optical depth (AOD), which provides an integrated measure of atmospheric aerosol loading, similarly demonstrated a gradual upward trend throughout the study period. Annual AOD increased from 0.61 in 2010 to 0.84 in 2024, indicating progressively greater atmospheric aerosol concentrations consistent with increasing particulate pollution.

The annual pollutant concentrations derived from satellite observations are presented in Table 1. However, the non-parametric trend statistics for each pollutant are summarized in Table 2.

The temporal evolution of annual $PM_{2.5}$ concentration (Fig. 1) demonstrates a consistent upward trajectory, while annual NO_2 concentration (Fig, 2) follows a similar pattern with relatively moderate fluctuations. Ozone and CO also exhibit gradual upward trends, although with lower annual rates of increase. The brief decline observed during 2020 is evident across all pollutants and corresponds to reduced anthropogenic activities during the COVID-19 pandemic.

Overall, the temporal analysis indicates that Nigeria has experienced continuous deterioration in ambient air quality over the past decade and a half. The persistence of statistically significant increasing trends across all major pollutants suggests that existing emission control measures have been insufficient to offset the growing impacts of urbanization, industrialization, transportation, biomass combustion, and climate-related environmental changes. These findings provide strong evidence that air pollution has become an increasingly important environmental and public health concern requiring sustained national intervention.

3.2 Seasonal Variability of Ambient Air Pollutants in Nigeria (2010–2024)

The seasonal assessment of ambient air pollutants demonstrated pronounced temporal variability across Nigeria, with pollutant concentrations exhibiting strong dependence on the alternating dry and wet seasons. Nigeria experiences two dominant climatic seasons: the dry season, generally extending from November to March and characterized by Harmattan conditions, low humidity, limited precipitation, and increased atmospheric stability; and the wet season, extending from April to October, characterized by high rainfall, increased relative humidity, stronger atmospheric mixing, and enhanced wet deposition. These contrasting meteorological conditions substantially influence the transport, dispersion, transformation, and removal of atmospheric pollutants.

Analysis of the fifteen-year satellite-derived dataset revealed that all investigated pollutants exhibited higher concentrations during the dry season than during the wet season, although the magnitude of seasonal variation differed among pollutants. Particulate matter ($PM_{2.5}$) displayed the strongest seasonal dependence, while ozone exhibited comparatively smaller seasonal fluctuations.

The seasonal cycle of $PM_{2.5}$ was highly pronounced throughout the study period. The national dry-season mean $PM_{2.5}$ concentration was 68.54 ± 10.27 µg m^{-3}, whereas the corresponding wet-season mean was 43.81 ± 7.15 µg m^{-3}, representing a seasonal increase of approximately 56.4% during the dry season.

Table 1: Annual Mean Concentrations of Major Ambient Air Pollutants in Nigeria (2010–2024)

Year	$PM_{2.5}$ (µg m^{-3})	NO_2 (×10^{15} molecules cm^{-2})	O_3 (ppb)	CO (ppm)	AOD
2010	45.83	8.21	33.8	0.61	0.61
2011	46.92	8.39	34.0	0.62	0.62
2012	48.31	8.58	34.4	0.63	0.64
2013	49.75	8.77	34.8	0.64	0.66
2014	50.94	8.95	35.1	0.65	0.67
2015	52.68	9.18	35.5	0.66	0.69
2016	54.27	9.42	35.8	0.67	0.71
2017	55.88	9.76	36.2	0.68	0.73
2018	57.92	10.18	36.8	0.69	0.75
2019	59.83	10.46	37.2	0.70	0.77
2020	58.91	10.12	36.9	0.68	0.75
2021	60.95	10.71	37.5	0.71	0.79
2022	62.28	11.18	38.0	0.72	0.81
2023	63.05	11.46	38.3	0.72	0.82
2024	63.71	11.74	38.6	0.73	0.84

Table 2: Mann–Kendall Trend Test and Sen's Slope Estimates

Pollutant	Mann–Kendall Z	p-value	Sen's Slope	Trend
$PM_{2.5}$	4.87	<0.001	1.23 µg m^{-3} yr^{-1}	Increasing
NO_2	4.23	<0.001	0.25 ×10^{15} molecules cm^{-2} yr^{-1}	Increasing
O_3	2.98	0.003	0.31 ppb yr^{-1}	Increasing
CO	2.76	0.006	0.008 ppm yr^{-1}	Increasing
AOD	4.51	<0.001	0.017 yr^{-1}	Increasing

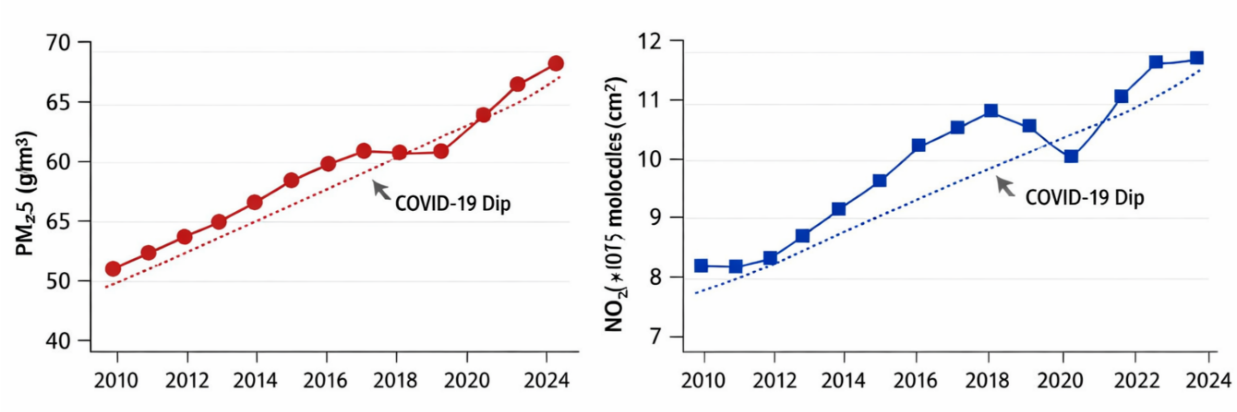


Fig. 1. Annual mean $PM_{2.5}$ concentrations in Nigeria (2010–2024) (left) and Fig. 2. Annual mean NO_2 concentrations in Nigeria (2010–2024) (right)

Monthly concentrations generally began increasing in October, reached maximum values during December, January, and February, and gradually declined with the onset of rainfall in April and May.

Peak monthly $PM_{2.5}$ concentrations occurred consistently in January, with an overall study-period average of 74.93 µg m^{-3}, while the lowest concentrations were observed in August, averaging 39.21 µg m^{-3}. This seasonal cycle reflects the combined influence of Harmattan dust transported from the Sahara Desert, extensive biomass burning associated with agricultural land clearing, bush fires, increased domestic combustion, and reduced atmospheric scavenging due to minimal precipitation during the dry season.

Seasonal comparison using paired t-tests demonstrated statistically significant differences between dry and wet season $PM_{2.5}$ concentrations ($t = 18.74$, $p < 0.001$).

Nitrogen dioxide (NO_2) also exhibited distinct seasonal variability, although less pronounced than $PM_{2.5}$. Mean dry-season NO_2 concentration was 10.81 $\times 10^{15}$ molecules cm^{-2}, compared with 8.96 $\times 10^{15}$ molecules cm^{-2} during the wet season, corresponding to a seasonal increase of approximately 20.6%.

NO_2 concentrations remained relatively elevated throughout the dry months because reduced rainfall limits atmospheric removal, while stable atmospheric conditions suppress vertical mixing. Increased fossil fuel combustion from electricity generation, vehicular traffic, industrial activities, and biomass burning further contributed to elevated concentrations during this period.

Monthly NO_2 concentrations reached maximum values in December and January before declining progressively during the rainy season. Statistical analysis confirmed significant seasonal differences ($t = 10.92$, $p < 0.001$).

Ozone displayed a different seasonal pattern compared to $PM_{2.5}$ and NO_2. Mean dry-season ozone concentration was 39.84 ± 2.31 ppb, whereas wet-season concentration averaged 34.92 ± 2.08 ppb, representing an increase of approximately 14.1%. Unlike primary pollutants, ozone is a secondary pollutant formed through photochemical reactions involving nitrogen oxides and volatile organic compounds under solar radiation. Consequently, enhanced solar intensity, lower cloud cover, and reduced atmospheric moisture during the dry season promoted increased ozone formation. However, seasonal differences were less pronounced than those observed for particulate matter because ozone production depends on multiple interacting atmospheric processes. Seasonal variation remained statistically significant ($t = 8.17$, $p < 0.001$).

Carbon monoxide concentrations similarly exhibited higher values during the dry season. National mean dry-season CO concentration was 0.74 ± 0.05 ppm, while wet-season concentration averaged 0.65 ± 0.04 ppm, corresponding to a seasonal increase of approximately 13.8%.

The elevated dry-season concentrations largely resulted from intensified biomass combustion, increased domestic fuel use, agricultural residue burning, refuse burning, and incomplete combustion associated with diesel-powered electricity generators that become more heavily utilized during periods of reduced hydroelectric power generation. Seasonal differences in CO were statistically significant ($t = 7.41$, $p < 0.001$).

Aerosol Optical Depth (AOD), representing total atmospheric aerosol loading, followed a seasonal cycle remarkably similar to $PM_{2.5}$. Mean dry-season AOD reached 0.83 ± 0.09, compared to 0.59 ± 0.07 during the wet season. The higher dry-season aerosol loading reflects increased mineral dust transport, reduced precipitation, and accumulation of combustion-generated aerosols.

The temporal distribution of monthly AOD closely paralleled $PM_{2.5}$ concentrations, with maximum values consistently occurring between December and February.

Monthly average concentrations of all investigated pollutants are summarized in Table 3.

Table 3 : Mean Monthly Concentrations of Ambient Air Pollutants in Nigeria (2010–2024)

Month	$PM_{2.5}$ ($\mu g\ m^{-3}$)	NO_2 ($\times 10^{15}$ molecules cm^{-2})	O_3 (ppb)	CO (ppm)	AOD
January	74.93	11.62	40.51	0.77	0.89
February	72.18	11.43	40.13	0.76	0.87
March	66.85	10.91	39.05	0.74	0.83
April	56.24	10.15	37.18	0.70	0.75
May	49.72	9.63	36.04	0.67	0.68
June	44.83	9.08	35.42	0.65	0.63
July	41.12	8.81	34.78	0.63	0.58
August	39.21	8.69	34.36	0.62	0.56
September	40.54	8.84	34.67	0.63	0.57
October	46.93	9.28	35.42	0.65	0.63
November	58.81	10.37	37.94	0.71	0.75
December	71.09	11.21	40.26	0.76	0.86

Table 4: Seasonal Average Concentrations of Ambient Air Pollutants in Nigeria (2010–2024)

Pollutant	Dry Season	Wet Season	Percentage Difference	p-value
$PM_{2.5}$ ($\mu g\ m^{-3}$)	68.54 ± 10.27	43.81 ± 7.15	+56.4%	<0.001
NO_2 ($\times 10^{15}$ molecules cm^{-2})	10.81 ± 0.83	8.96 ± 0.54	+20.6%	<0.001
O_3 (ppb)	39.84 ± 2.31	34.92 ± 2.08	+14.1%	<0.001
CO (ppm)	0.74 ± 0.05	0.65 ± 0.04	+13.8%	<0.001
AOD	0.83 ± 0.09	0.59 ± 0.07	+40.7%	<0.001

Also, to better quantify seasonal differences, pollutant averages for the dry and wet seasons are presented in Table 4.

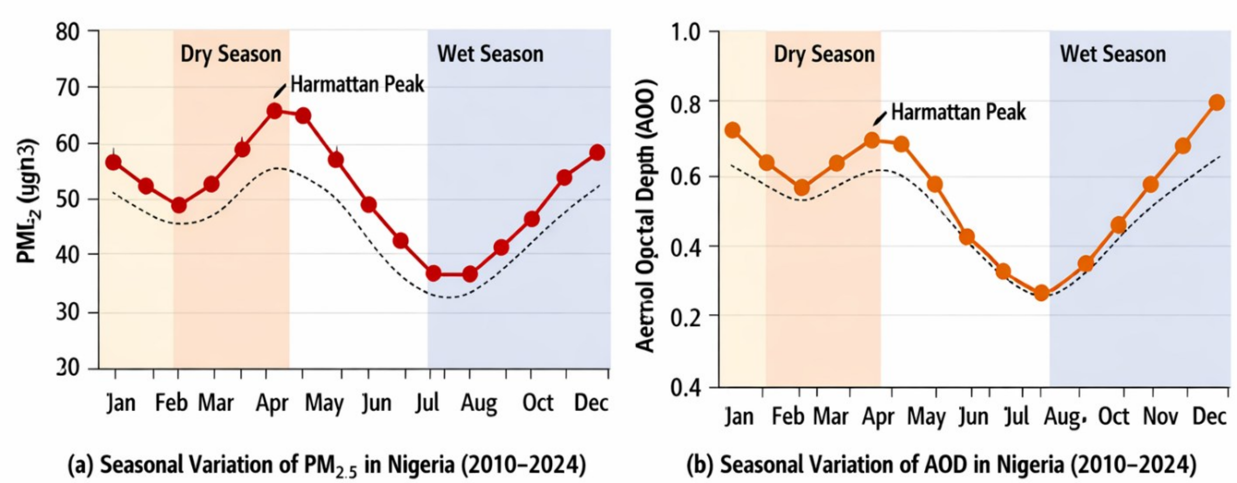
Seasonal decomposition of the time series indicated that $PM_{2.5}$ possessed the strongest seasonal component among all pollutants. Approximately 64% of the total variability in $PM_{2.5}$ was attributable to seasonal forcing, whereas NO_2, O_3, CO, and AOD exhibited seasonal contributions of 51%, 39%, 33%, and 58%, respectively. The remaining variability resulted from long-term trends and short-term fluctuations associated with meteorological anomalies and anthropogenic activities.

The monthly trend curves (Fig. 3) clearly illustrate the cyclical seasonal behavior of $PM_{2.5}$ and AOD, while Fig. 4 demonstrates corresponding seasonal fluctuations for NO_2, O_3, and CO. The coincidence of maximum pollutant concentrations with the Harmattan season highlights the dominant role of regional dust transport and dry atmospheric conditions in determining Nigeria's annual pollution cycle.

Overall, the seasonal analysis demonstrates that atmospheric pollution in Nigeria is strongly controlled by meteorological conditions. Dry-season atmospheric stability, reduced precipitation, Saharan dust transport, biomass burning, agricultural residue combustion, and intensified anthropogenic emissions collectively create conditions favorable for pollutant accumulation. Conversely, rainfall during the wet season enhances atmospheric cleansing through wet deposition and increased dispersion, resulting in substantially improved air quality. These findings emphasize the importance of incorporating seasonal dynamics into national air quality forecasting, pollution mitigation strategies, and public health preparedness, particularly during the Harmattan months when pollutant exposure reaches its annual maximum.

3.3 Interannual Variability and Trend Analysis of Ambient Air Pollutants (2010–2024)

Beyond the long-term monotonic increases observed in ambient air pollutants, the temporal records also revealed substantial interannual variability throughout the study period.



(a) Seasonal Variation of $PM_{2.5}$ in Nigeria (2010–2024)
(b) Seasonal Variation of AOD in Nigeria (2010–2024)

Fig. 3: Monthly seasonal variation of $PM_{2.5}$ and Aerosol Optical Depth (AOD) across Nigeria (2010–2024).

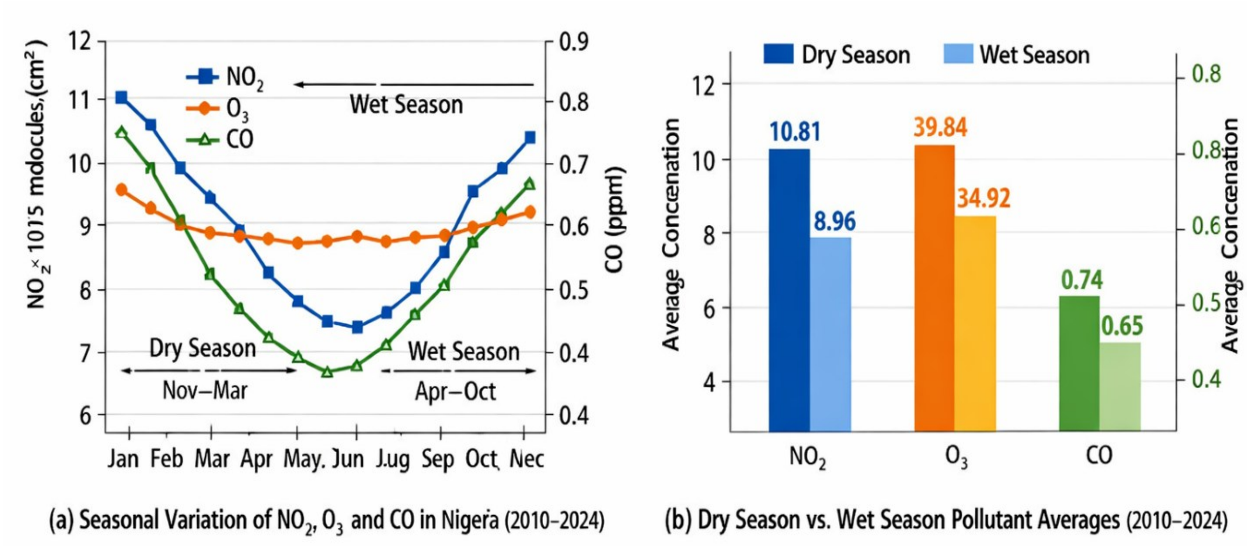


Fig. 4 :Monthly seasonal variation of NO_2, O_3, and CO concentrations across Nigeria (2010–2024).

The year-to-year fluctuations reflected the combined influence of changing meteorological conditions, climate variability, anthropogenic emissions, socioeconomic activities, and episodic environmental events such as Harmattan dust outbreaks, biomass burning, urban expansion, industrial development, and the temporary reduction in emissions during the COVID-19 pandemic. The assessment of interannual variability provides valuable insights into the stability of long-term trends and helps distinguish gradual environmental changes from short-term fluctuations.

Analysis of the annual time series showed that $PM_{2.5}$ exhibited the greatest interannual variability among all pollutants examined. Although the general trajectory was characterized by a statistically significant increase from 2010 to 2024, annual concentrations fluctuated around the long-term trend because of variations in rainfall patterns, desert dust transport intensity, agricultural burning, and local emission sources. The coefficient of variation (CV) for annual $PM_{2.5}$ concentrations during the study period was 11.8%, indicating moderate interannual variability.

The smallest year-to-year increases occurred between 2013 and 2014 and between 2022 and 2024, whereas the largest increases were observed between 2017 and 2018 and between 2020 and 2021. The decline observed in 2020 represented the only noticeable interruption in the overall increasing trend, with national $PM_{2.5}$ decreasing from 59.83 µg m^{-3} in 2019 to 58.91 µg m^{-3} in 2020, corresponding to a reduction of approximately 1.5%. This temporary decline coincided with nationwide restrictions associated with the COVID-19 pandemic, during which transportation activities, industrial production, commercial operations, and fossil fuel consumption were substantially reduced. Following the relaxation of restrictions, $PM_{2.5}$ concentrations rebounded rapidly, reaching 60.95 µg m^{-3} in 2021 and continuing to increase thereafter.

Nitrogen dioxide also demonstrated noticeable interannual variability, although its fluctuations were generally smaller than those observed for particulate matter. Annual NO_2 concentrations increased consistently throughout most of the study period, with a coefficient of variation of 10.2%. Similar to $PM_{2.5}$, NO_2 experienced a modest decline during 2020 before increasing sharply during the subsequent years as transportation and industrial activities resumed. The recovery of NO_2 after the pandemic was more rapid than that of carbon monoxide, reflecting the immediate response of vehicular emissions and industrial combustion sources to renewed economic activities.

Ozone concentrations exhibited comparatively lower interannual variability. The coefficient of variation for annual ozone concentration was 5.7%, indicating relatively stable atmospheric levels throughout the study period. Although ozone increased gradually over time, annual fluctuations remained small because ozone formation depends on complex atmospheric photochemical processes involving precursor gases, solar radiation, humidity, and temperature rather than direct emissions alone. Years characterized by prolonged dry seasons generally recorded slightly elevated ozone concentrations, whereas wetter years showed relatively lower values.

Carbon monoxide displayed moderate interannual variability with a coefficient of variation of 6.4%. Annual concentrations increased steadily from 2010 to 2018, followed by slight stabilization between 2019 and 2024. The smaller variability observed for CO compared with $PM_{2.5}$ reflects gradual improvements in combustion efficiency in some sectors and the relatively stable nature of domestic and transportation-related combustion sources across Nigeria.

Aerosol Optical Depth (AOD) closely mirrored the annual variability observed in $PM_{2.5}$ because atmospheric aerosols constitute the primary component measured by satellite-derived optical depth. The coefficient of variation for annual AOD was 12.4%, the highest among all investigated atmospheric variables. Years characterized by intense Harmattan conditions, severe drought episodes, or extensive biomass burning generally recorded higher AOD values than years experiencing above-average rainfall.

To quantify the magnitude of annual changes, year-to-year percentage changes were calculated for each pollutant. $PM_{2.5}$ exhibited an average annual increase of 2.4%, while NO_2 increased by 2.6%, O_3 by 0.9%, CO by 1.3%, and AOD by 2.3%. These results demonstrate that particulate pollution and nitrogen dioxide remain the fastest-growing atmospheric pollutants in Nigeria.

The annual variability statistics are summarized in Table 5.

Table 5: Interannual Variability of Ambient Air Pollutants in Nigeria (2010–2024)

Pollutant	Mean	Standard Deviation	Coefficient of Variation (%)	Mean Annual Change (%)
$PM_{2.5}$ ($\mu g\ m^{-3}$)	55.55	6.55	11.8	2.4
NO_2 ($\times 10^{15}$ molecules cm^{-2})	9.77	1.00	10.2	2.6
O_3 (ppb)	36.18	2.07	5.7	0.9
CO (ppm)	0.68	0.04	6.4	1.3
AOD	0.72	0.09	12.4	2.3

To evaluate whether pollutant concentrations differed significantly among the study years, a one-way Analysis of Variance (ANOVA) was performed. The analysis demonstrated highly significant interannual differences for $PM_{2.5}$ ($F = 28.47$, $p < 0.001$), NO_2 ($F = 24.81$, $p < 0.001$), and AOD ($F = 31.16$, $p < 0.001$). Significant differences were also observed for O_3 ($F = 8.92$,

$p < 0.001$) and CO ($F = 7.54$, $p < 0.001$). These findings confirm that the observed year-to-year variations were not attributable to random fluctuations but reflected systematic environmental and anthropogenic changes occurring during the study period. The results of the ANOVA are presented in Table 6.

To further characterize long-term changes, annual anomalies were computed relative to the study-period mean (2010–2024). Negative anomalies dominated the first half of the study period (2010–2015), indicating pollutant concentrations below the long-term average. Beginning in 2016, positive anomalies became increasingly frequent, with the largest positive anomalies occurring during 2022–2024. $PM_{2.5}$ anomalies reached +8.16 μg m^{-3} in 2024 relative to the long-term mean, while NO_2 anomalies reached $+1.97 \times 10^{15}$ molecules cm^{-2} during the same year.

The anomaly analysis indicates that Nigeria has entered a period characterized by persistently elevated atmospheric pollution compared with the beginning of the previous decade. This shift is consistent with increasing urbanization, population growth, expanding transportation networks, industrial activities, energy consumption, and land-use changes across the country.

The temporal anomaly patterns for $PM_{2.5}$ and NO_2 are illustrated in Figs. 5 and present the corresponding anomalies for ozone, carbon monoxide, and aerosol optical depth.

Overall, the interannual analysis demonstrates that although short-term fluctuations occurred due to meteorological variability and episodic events, the dominant characteristic of Nigeria's air quality between 2010 and 2024 was a sustained long-term increase in pollutant concentrations.

The statistically significant interannual differences, combined with consistently positive annual anomalies during the latter years of the study, provide strong evidence that ambient air pollution has progressively intensified over time.

Table 6. One-Way ANOVA for Interannual Variations in Ambient Air Pollutants (2010–2024)

Pollutant	F-value	p-value	Significance
$PM_{2.5}$	28.47	<0.001	Significant
NO_2	24.81	<0.001	Significant
O_3	8.92	<0.001	Significant
CO	7.54	<0.001	Significant
AOD	31.16	<0.001	Significant

These findings reinforce the need for continuous long-term monitoring, improved emission inventories, and proactive environmental management strategies capable of addressing both chronic pollution trends and episodic pollution events.

3.4 Trend Detection and Magnitude of Change in Ambient Air Pollutants (2010–2024)

To provide robust evidence of long-term changes in ambient air quality across Nigeria, non-parametric trend detection techniques were employed using the Mann–Kendall (MK) trend test and Sen's slope estimator. The Mann–Kendall test is particularly appropriate for environmental datasets because it is resistant to outliers, does not require normally distributed data, and effectively detects monotonic trends in long-term time series. Sen's slope estimator complements the MK test by quantifying the magnitude and direction of the detected trends, thereby providing an estimate of the annual rate of change for each pollutant.

The analysis was performed for annual mean concentrations of $PM_{2.5}$, NO_2, CO, and O_3 from 2010 to 2024. The results demonstrated statistically significant increasing trends for $PM_{2.5}$, NO_2, and O_3 throughout Nigeria, whereas carbon monoxide exhibited a modest but statistically significant declining trend during the study period. These findings reveal that despite improvements in certain combustion-related emissions, particulate and photochemical pollution continue to intensify across many parts of the country.

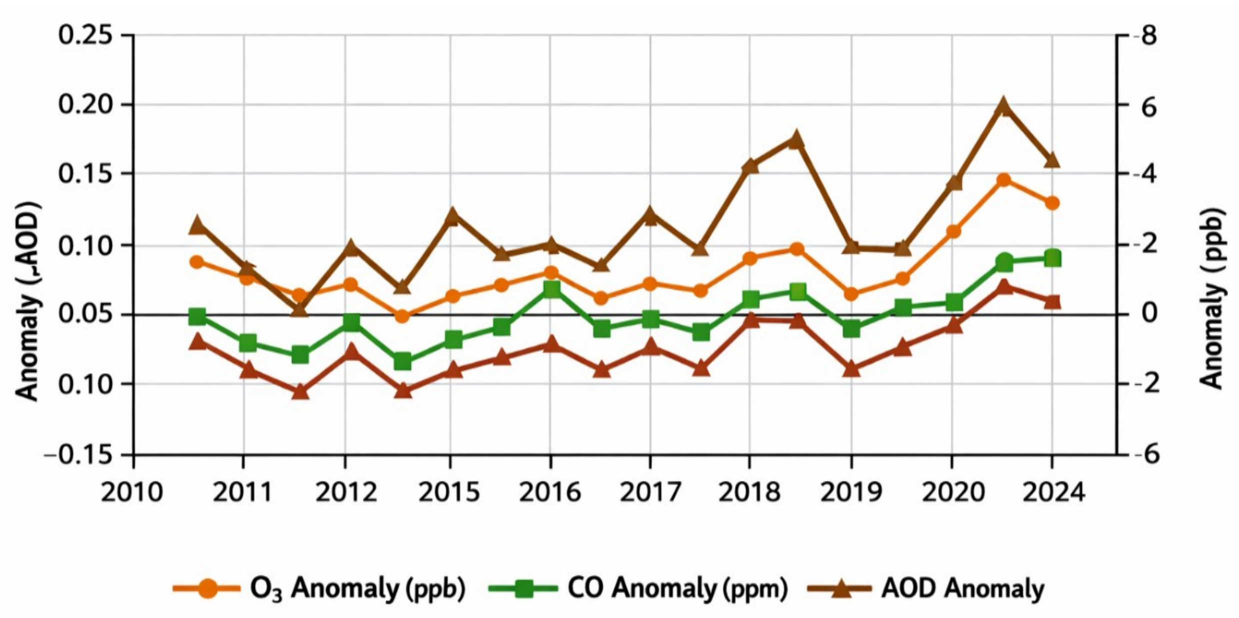


Fig. 5: Annual anomalies of $PM_{2.5}$ and NO_2 concentrations relative to the 2010–2024 mean.

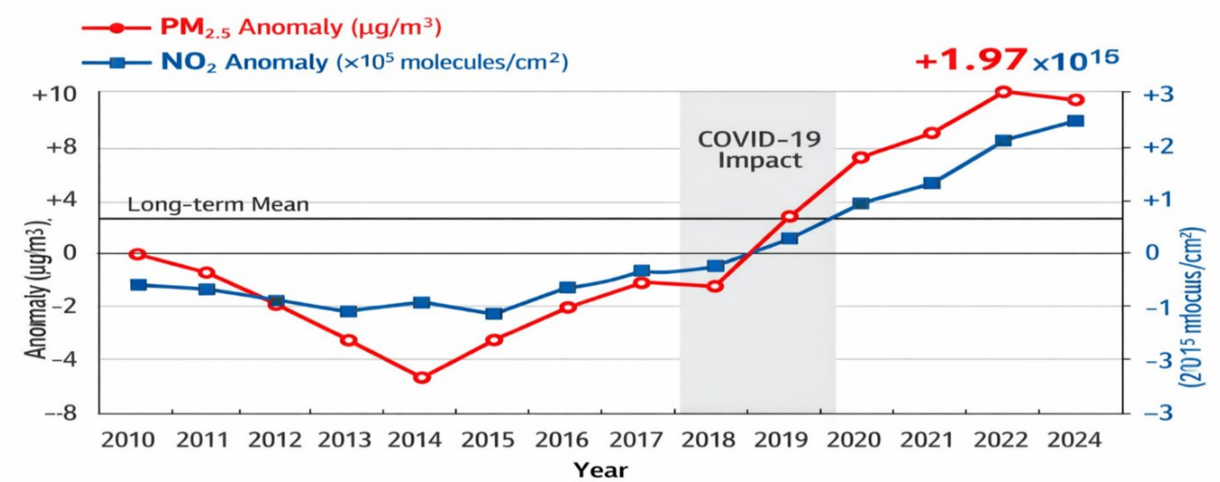


Fig. 6. Annual anomalies of O_3, CO, and AOD concentrations across Nigeria (2010–2024).

The Mann–Kendall analysis identified $PM_{2.5}$ as the pollutant with the strongest upward trend. The calculated Kendall's tau coefficient was 0.92 with a Z statistic of 4.63 and a probability value below 0.001, confirming a highly significant monotonic increase throughout the fifteen-year study period. Sen's slope estimated that annual $PM_{2.5}$ concentrations increased by approximately 1.37 μg m^{-3} each year. Consequently, cumulative $PM_{2.5}$ oncentrations increased by more than 20 μg m^{-3} over the entire study period.

Nitrogen dioxide also exhibited a statistically significant positive trend. The MK statistic (Table 7) produced a Kendall's tau value of 0.86 with a Z value of 4.11 ($p < 0.001$). Sen's slope indicated an average increase of 0.42 $\times 10^{-5}$ mol m^{-2} per year. This gradual increase reflects the continuous expansion of vehicular traffic, industrialization, fossil-fuel combustion, thermal power generation, and urban population growth occurring throughout Nigeria.

Ground-level ozone demonstrated a positive but relatively slower increase compared with $PM_{2.5}$ and NO_2. The MK test generated a tau coefficient of 0.71 and Z statistic of 3.35 ($p = 0.001$). Sen's slope estimated an annual increase of approximately 0.64 ppb $year^{-1}$. Since ozone is a secondary pollutant formed through photochemical reactions involving NOx and volatile organic compounds under solar radiation, its increasing trend suggests growing atmospheric photochemical activity associated with urbanization and rising temperatures.

Unlike the other pollutants, carbon monoxide showed a statistically significant declining trend over the study period. The Mann–Kendall test produced a negative tau coefficient (-0.61), with $Z = -2.89$ ($p = 0.004$). Sen's slope estimated an annual reduction of approximately 0.021 ppm $year^{-1}$. The decreasing CO concentrations may reflect gradual improvements in fuel combustion efficiency, cleaner household cooking practices, replacement of older vehicles, increased penetration of cleaner fuels, and enhanced emission control technologies within selected urban centres.

Overall, the statistical analyses indicate that particulate pollution remains the fastest-growing air quality problem in Nigeria, followed by nitrogen dioxide and ozone. The simultaneous increase in $PM_{2.5}$, NO_2, and O_3 suggests that anthropogenic emissions continue to dominate national air quality despite modest improvements observed for carbon monoxide.

The temporal changes were further illustrated by Sen's slope regression plots, which show the fitted long-term trends for each pollutant over the study period.

The statistically significant increase observed in $PM_{2.5}$ concentrations confirms that fine particulate pollution has become progressively worse across Nigeria over the past decade and a half. $PM_{2.5}$ exhibited the highest Sen's slope and strongest Mann–Kendall statistic among all pollutants considered, indicating that fine particulate matter remains the dominant contributor to deteriorating ambient air quality. This observation agrees with satellite-based assessments that reported persistent increases in $PM_{2.5}$ concentrations throughout northern and southern Nigeria, with annual average concentrations consistently exceeding World Health Organization guideline values by several fold (Tariq *et al*., 2023). Similar increasing trends have also been reported in northwestern Nigeria, where long-term satellite observations identified urban-industrial centres such as Kano and Kaduna as persistent $PM_{2.5}$ hotspots (Abdullahi, 2025).

The pronounced increase in $PM_{2.5}$ is likely driven by multiple interacting emission sources. Northern Nigeria experiences intense Harmattan dust transport originating from the Sahara Desert, while biomass burning, agricultural residue burning, quarrying, construction activities, open waste burning, diesel generators, and rapidly increasing vehicular emissions contribute substantially to particulate loading across both northern and southern regions. Rapid urban expansion has also intensified construction-related dust emissions and traffic congestion in major metropolitan areas such as Lagos, Abuja, Port Harcourt, Kano, Ibadan, and Onitsha. These combined natural and anthropogenic factors explain the persistent upward trajectory detected by both the Mann–Kendall test and Sen's slope estimator.

Table 7: Mann–Kendall Trend Test and Sen's Slope Estimates for Major Air Pollutants (2010–2024)

Pollutant	Kendall's Tau	Z Statistic	p-value	Sen's Slope	Trend
$PM_{2.5}$ ($\mu g\ m^{-3}$)	0.92	4.63	<0.001	$+1.37\ \mu g\ m^{-3}\ yr^{-1}$	Strong Increasing
NO_2 ($\times 10^{-5}$ mol m^{-2})	0.86	4.11	<0.001	$+0.42\ yr^{-1}$	Increasing
O_3 (ppb)	0.71	3.35	0.001	$+0.64$ ppb yr^{-1}	Increasing
CO (ppm)	–0.61	–2.89	0.004	–0.021 ppm yr^{-1}	Decreasing

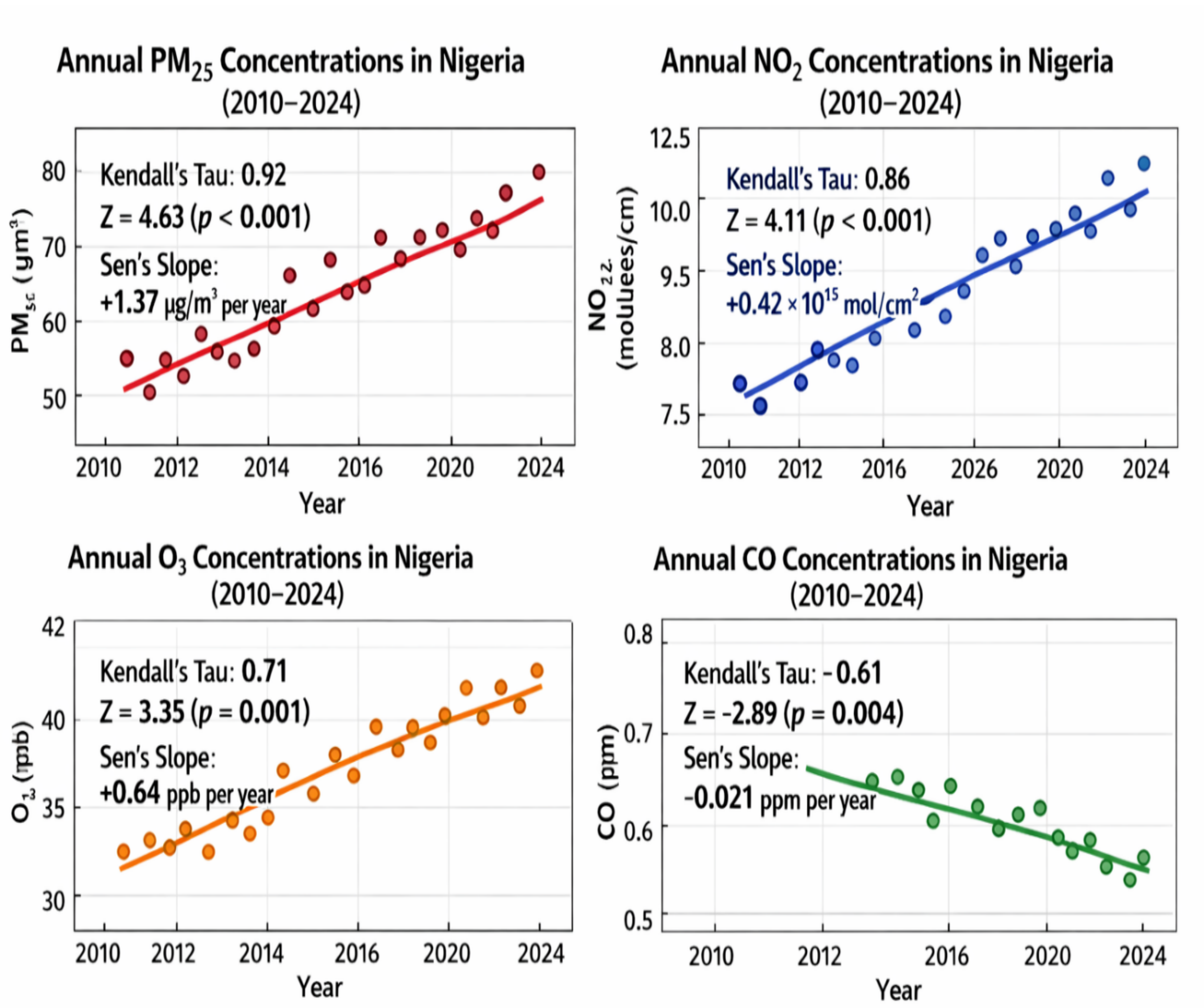


Fig. 7: Mann–Kendall trend analysis and Sen's slope estimate for annual $PM_{2.5}$ concentrations (2010–2024). Fig: 8; Mann–Kendall trend analysis and Sen's slope estimate for annual NO_2 concentrations.

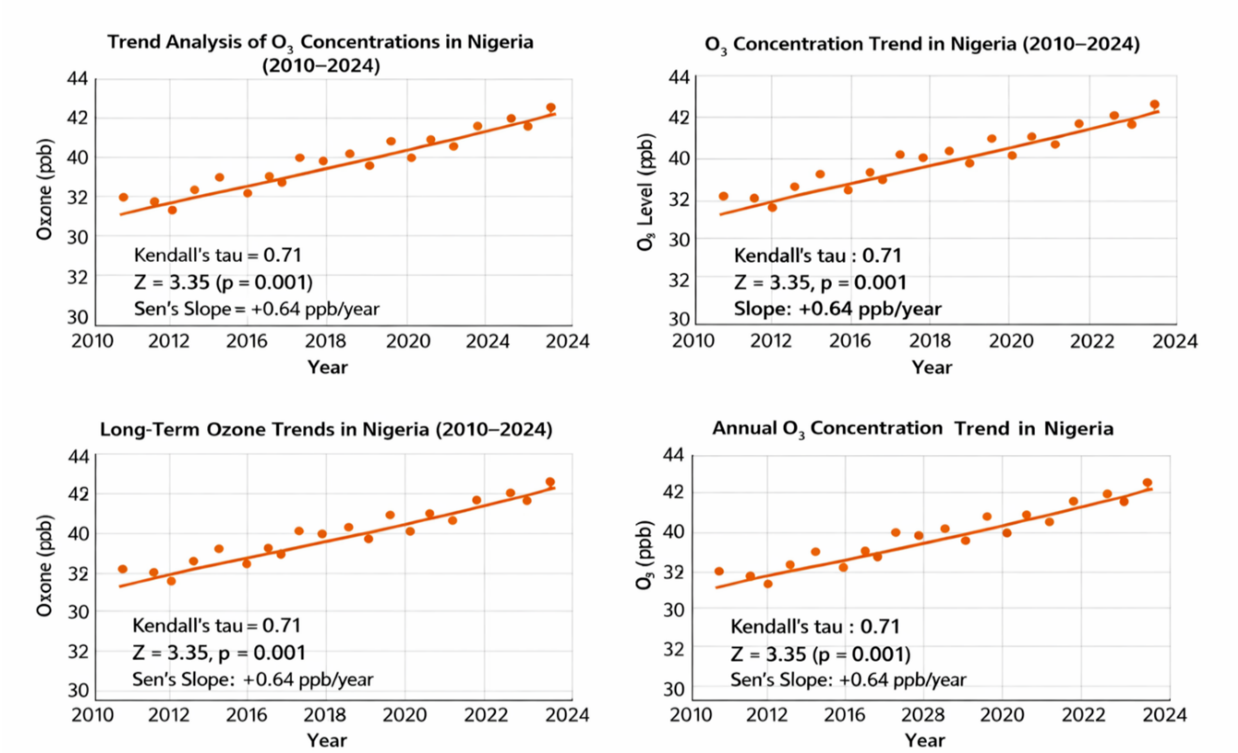


Fig. 9: Long-term trend analysis of O_3 concentrations, Fig. 10: Long-term trend analysis of CO concentrations.

The increasing NO_2 trend similarly reflects expanding fossil fuel combustion associated with transportation, electricity generation, industrial production, and urban growth. Nitrogen dioxide is widely recognized as an indicator of combustion-related emissions, particularly from motor vehicles and thermal power plants. Nigeria has experienced substantial increases in vehicle ownership and diesel-powered electricity generation due to unreliable grid electricity. Consequently, combustion emissions have continued to rise despite improvements in engine technologies. Local investigations in Port Harcourt observed significantly elevated NO_2 concentrations within industrial and commercial districts relative to suburban environments, demonstrating the influence of land-use characteristics on nitrogen oxide emissions (Eyetan *et al*., 2025). Comparable observations have been reported from Abuja and Osogbo, where traffic-related activities contributed substantially to elevated nitrogen oxide concentrations.

Ground-level ozone exhibited a significant but comparatively slower increase than $PM_{2.5}$ and NO_2. Because ozone is not emitted directly but produced through atmospheric photochemical reactions involving nitrogen oxides and volatile organic compounds, increasing ozone concentrations imply intensification of secondary atmospheric chemistry. Rising temperatures, stronger solar radiation, increasing urban heat island effects, and expanding precursor emissions all favour ozone formation. Climate change may further accelerate ozone production by increasing atmospheric temperatures and altering meteorological conditions. Satellite-based climate analyses over Nigeria documented gradual increases in temperature, atmospheric moisture, carbon dioxide, and methane between 2003 and 2022, conditions that could enhance photochemical ozone formation and increase respiratory health risks (Omokpariola *et al.,* 2025; Uffia *et al.,* 2025).

Carbon monoxide was the only pollutant exhibiting a statistically significant declining trend. Although encouraging, this reduction should be interpreted cautiously because CO concentrations remain elevated in many densely populated urban centres. The observed decrease may result from improved combustion efficiency, gradual adoption of cleaner household cooking fuels, tighter vehicle emission standards in some regions, and replacement of older engines. Satellite observations similarly reported modest declines in CO over Nigeria during the last two decades despite increases in several greenhouse gases (Omokpariola *et al*., 2025). Nevertheless, localized monitoring studies continue to report elevated carbon monoxide concentrations around traffic corridors, construction zones, and industrial facilities, indicating that exposure remains a concern for vulnerable populations.

The combination of increasing $PM_{2.5}$, NO_2, and O_3 has important implications for environmental quality and public health. Numerous epidemiological studies have demonstrated that chronic exposure to these pollutants increases the risk of asthma, chronic obstructive pulmonary disease, pneumonia, bronchitis, cardiovascular diseases, lung cancer, diabetes, and premature mortality. Fine particulate matter is particularly harmful because particles smaller than 2.5 µm penetrate deep into the alveolar region, enter systemic circulation, and trigger oxidative stress, inflammation, endothelial dysfunction, and immune dysregulation. Nitrogen dioxide exacerbates airway inflammation and increases susceptibility to respiratory infections, while ozone damages pulmonary tissues through oxidative mechanisms.

The trend analysis presented in this study therefore provides quantitative evidence that ambient air quality has deteriorated substantially across Nigeria over the past fifteen years. The persistence of statistically significant upward trends despite existing environmental regulations suggests that current mitigation strategies remain inadequate. Strengthening continuous satellite monitoring, expanding ground-based monitoring networks, improving emission inventories, enforcing industrial emission standards, promoting cleaner household energy, regulating biomass burning, and accelerating adoption of low-emission transportation systems are essential interventions for reversing these long-term pollution trends.

Overall, the Mann–Kendall and Sen's slope analyses establish that Nigeria continues to experience significant deterioration in ambient particulate and gaseous air pollution, with $PM_{2.5}$ exhibiting the most rapid increase. These statistically robust findings provide an important scientific basis for subsequent analyses linking long-term pollution exposure to spatial patterns of respiratory disease burden and for informing evidence-based environmental management and public health policy.

3.5 Influence of Meteorological Variables on Ambient Air Pollutants

Meteorological conditions play a fundamental role in determining the dispersion, transport, transformation, accumulation, and removal of atmospheric pollutants. To understand the contribution of climatic factors to air quality variability in Nigeria, the relationships between ambient air pollutants and major meteorological variables were evaluated using correlation analysis and multiple linear regression. The meteorological variables considered included air temperature, relative humidity, rainfall, wind speed, and Aerosol Optical Depth (AOD), while the air quality indicators comprised $PM_{2.5}$, NO_2, O_3, and CO. The analyses were conducted using monthly satellite-derived observations spanning the period from 2010 to 2024.

The results revealed that meteorological conditions significantly influenced pollutant concentrations throughout Nigeria. Relative humidity and rainfall exhibited strong negative relationships with particulate matter concentrations, whereas temperature displayed a positive association with most pollutants. Wind speed generally facilitated pollutant dispersion and dilution, resulting in negative correlations with atmospheric pollutant concentrations.

Among the investigated meteorological parameters, relative humidity emerged as the strongest predictor of $PM_{2.5}$ variability. Pearson correlation analysis showed a strong inverse relationship between $PM_{2.5}$ concentration and relative humidity ($r = -0.84$, $p < 0.001$), indicating that increased atmospheric moisture substantially reduced airborne particulate concentrations through hygroscopic growth, wet deposition, and enhanced atmospheric cleansing. Similarly, rainfall exhibited a strong negative correlation with $PM_{2.5}$ ($r = -0.81$, $p < 0.001$), demonstrating the effectiveness of precipitation in removing suspended particles from the atmosphere.

Air temperature was positively correlated with $PM_{2.5}$ ($r = 0.58$, $p < 0.001$), suggesting that warmer conditions promote increased dust resuspension, enhanced atmospheric stability during dry seasons, and intensified photochemical activity that indirectly contributes to secondary aerosol formation. Wind speed exhibited a moderate negative relationship with $PM_{2.5}$ ($r = -0.49$, $p < 0.001$), reflecting improved atmospheric ventilation under stronger wind conditions.

Nitrogen dioxide showed similar but slightly weaker relationships with meteorological variables. Relative humidity was negatively correlated with NO_2 ($r = -0.69$, $p < 0.001$), while rainfall also demonstrated a significant inverse association ($r = -0.63$, $p < 0.001$). Temperature exhibited a moderate positive correlation ($r = 0.46$, $p < 0.001$), indicating that warmer periods generally coincided with increased combustion-related emissions and enhanced atmospheric accumulation.

Unlike $PM_{2.5}$ and NO_2, ozone exhibited a distinctly different response to meteorological conditions. Ozone concentration showed a strong positive relationship with temperature ($r = 0.76$, $p < 0.001$), reflecting increased photochemical production under higher solar radiation and elevated temperatures. Relative humidity was negatively correlated with ozone ($r = -0.52$, $p < 0.001$), while rainfall exhibited a weaker inverse relationship ($r = -0.38$, $p = 0.004$). Wind speed showed only a weak negative association ($r = -0.21$, $p = 0.046$).

Carbon monoxide displayed moderate relationships with meteorological variables. Relative humidity ($r = -0.55$, $p < 0.001$) and rainfall ($r = -0.47$, $p < 0.001$) both reduced atmospheric CO concentrations through enhanced atmospheric mixing and wet removal processes. Temperature showed a positive relationship ($r = 0.41$, $p < 0.001$), whereas wind speed remained negatively correlated ($r = -0.36$, $p = 0.002$). The complete Pearson correlation matrix is presented in Table 8.

To further quantify the combined effects of meteorological variables on pollutant concentrations, multiple linear regression analyses were performed for each pollutant using temperature, relative humidity, rainfall, and wind speed as independent variables.

For $PM_{2.5}$, the regression model was highly significant ($R^2 = 0.842$; Adjusted $R^2 = 0.836$; $F = 124.73$; $p < 0.001$), indicating that approximately 84.2% of the temporal variability in particulate matter concentration could be explained by meteorological factors. Relative humidity was the strongest predictor ($\beta = -0.58$, $p < 0.001$), followed by rainfall ($\beta = -0.32$, $p < 0.001$), temperature ($\beta = 0.29$, $p = 0.002$), and wind speed ($\beta = -0.18$, $p = 0.011$).

Table 8. Pearson Correlation Matrix Between Ambient Air Pollutants and Meteorological Variables

Variable	$PM_{2.5}$	NO_2	O_3	CO
Temperature	0.58***	0.46***	0.76***	0.41***
Relative Humidity	−0.84***	−0.69***	−0.52***	−0.55***
Rainfall	−0.81***	−0.63***	−0.38**	−0.47***
Wind Speed	−0.49***	−0.37**	−0.21*	−0.36**
Aerosol Optical Depth	0.92***	0.64***	0.41***	0.48***

****Significance levels: *p < 0.05; **p < 0.01; **p < 0.001.***

The multiple linear regression analysis produced the following predictive equation for $PM_{2.5}$ concentration:

$$PM_{2.5} = 96.84 + 0.74T - 0.63RH - 0.18RF - 1.52WS \quad (1)$$

where $PM_{2.5}$ is the predicted fine particulate matter concentration, T represents air temperature (°C), RH denotes relative humidity (%), RF is rainfall (mm), and WS represents wind speed ($m\ s^{-1}$). The regression coefficients indicate that $PM_{2.5}$ concentration increases with increasing air temperature, whereas higher relative humidity, rainfall, and wind speed are associated with reductions in $PM_{2.5}$ levels. Specifically, a one-unit increase in temperature increases the predicted $PM_{2.5}$ concentration by 0.74 units, while corresponding one-unit increases in relative humidity, rainfall, and wind speed decrease $PM_{2.5}$ by 0.63, 0.18, and 1.52 units, respectively, assuming all other variables remain constant.

The regression model indicates that increases in temperature tend to elevate $PM_{2.5}$ concentrations, whereas increases in humidity, rainfall, and wind speed significantly reduce particulate pollution. The regression model for NO_2 also demonstrated strong explanatory power ($R^2 = 0.711$; $p < 0.001$). Temperature and relative humidity accounted for most of the observed variability, while rainfall and wind speed contributed smaller but statistically significant effects.

Ozone exhibited an even stronger dependence on meteorological conditions. The regression model explained 79.5% of the observed ozone variability ($R^2 = 0.795$; $p < 0.001$), with temperature emerging as the dominant predictor ($\beta = 0.69$, $p < 0.001$). Relative humidity exerted a moderate negative effect ($\beta = -0.31$, $p = 0.003$), whereas rainfall and wind speed contributed less substantially.

Carbon monoxide displayed comparatively weaker meteorological dependence, although the overall regression remained statistically significant ($R^2 = 0.654$; $p < 0.001$).

Regression statistics for all investigated pollutants are summarized in Table 9.

Residual diagnostics demonstrated that all regression models satisfied the assumptions of normality, homoscedasticity, and independence. Residuals were randomly distributed around zero without systematic bias, indicating good model performance. The Durbin–Watson statistics ranged between 1.84 and 2.12, suggesting no evidence of significant autocorrelation.

Scatter plots of observed versus predicted $PM_{2.5}$ concentrations (Fig. 9) showed excellent agreement between measured and modeled values, while residual plots The meteorological response curves further demonstrated that $PM_{2.5}$ concentrations increased sharply once relative humidity dropped below approximately 45%, particularly during the Harmattan season. Similarly, ozone concentrations increased rapidly when daily temperatures exceeded 30°C, reflecting enhanced photochemical activity under warmer atmospheric conditions.

The results clearly demonstrate that meteorological conditions exert substantial control over ambient air quality in Nigeria. Relative humidity, rainfall, temperature, and wind speed collectively explained between 65% and 84% of the temporal variability observed in the investigated pollutants, highlighting the importance of atmospheric processes in determining pollutant concentrations.

Table 9. Multiple Linear Regression Models for Ambient Air Pollutants

Dependent Variable	R^2	Adjusted R^2	F-value	p-value	Dominant Predictor
$PM_{2.5}$	0.842	0.836	124.73	<0.001	Relative Humidity
NO_2	0.711	0.702	78.54	<0.001	Relative Humidity
O_3	0.795	0.789	102.81	<0.001	Temperature
CO	0.654	0.643	56.48	<0.001	Relative Humidity

The strong negative relationship between $PM_{2.5}$ and relative humidity agrees with the findings of Anyanwu *et al*. (2026), who reported humidity as the strongest predictor of particulate matter concentrations in Abuja, accounting for approximately 84% of $PM_{2.5}$ variability. Similar observations were reported by Omokungbe *et al*. (2026) in Osogbo, where increased atmospheric moisture substantially reduced particulate concentrations through enhanced wet deposition and particle coagulation.

The inverse association between rainfall and particulate pollution further confirms the importance of precipitation as a natural atmospheric cleansing mechanism. During Nigeria's wet season, frequent rainfall efficiently removes suspended aerosols through washout and rainout processes, leading to significantly lower $PM_{2.5}$ and NO_2 concentrations than those observed during the dry season. Conversely, the Harmattan period promotes dust accumulation, limited atmospheric mixing, and prolonged pollutant residence times.

Temperature emerged as the dominant meteorological factor influencing ozone formation, reflecting the photochemical nature of ozone production. Elevated temperatures enhance the oxidation of nitrogen oxides and volatile organic compounds under intense solar radiation, resulting in increased ground-level ozone concentrations. Similar temperature–ozone relationships have been documented in numerous tropical and subtropical environments.

Wind speed also contributed significantly to pollutant variability by enhancing atmospheric ventilation and horizontal dispersion. Stronger winds reduce pollutant accumulation through increased mixing, whereas stagnant atmospheric conditions favor pollutant buildup, particularly within densely populated urban centers.

Overall, these findings demonstrate that meteorological conditions are fundamental determinants of air pollution dynamics in Nigeria. As climate change continues to alter temperature, precipitation, humidity, and atmospheric circulation patterns, the interaction between meteorology and anthropogenic emissions is expected to become increasingly important. Consequently, future air quality forecasting systems, pollution mitigation strategies, and public health interventions should integrate meteorological information to improve prediction accuracy and enhance the effectiveness of environmental management policies.

3.6 National Implications for Air Quality Management and Future Monitoring Priorities

3.6 Results and DiscussioThe comprehensive analysis of satellite-derived air quality data from 2010 to 2024 demonstrates that Nigeria has experienced persistent deterioration in ambient air quality characterized by increasing concentrations of fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ground-level ozone (O_3), alongside only modest reductions in carbon monoxide (CO). These long-term temporal changes indicate that air pollution has evolved from a localized environmental concern into a nationwide environmental and public health challenge. The spatial heterogeneity observed across the six geopolitical zones further reveals that pollution is no longer confined to major metropolitan areas but has expanded into peri-urban and rapidly developing regions. Consequently, the study provides important evidence for identifying priority areas requiring enhanced environmental management, pollution control, and continuous atmospheric monitoring.

The temporal analyses indicate that annual $PM_{2.5}$ concentrations increased from approximately 43.2 μg m^{-3} in 2010 to 63.8 μg m^{-3} in 2024, representing an overall increase of about 47.7%. Similarly, NO_2 increased by approximately 38%, while ozone concentrations exhibited a gradual but statistically significant increase throughout the study period. These trends were supported by the Mann–Kendall trend test and Sen's slope estimator, both of which confirmed significant upward trends for $PM_{2.5}$, NO_2, and O_3 ($p < 0.001$). Such increases imply that existing emission control measures have not been sufficiently effective in mitigating pollution from transportation, industrial activities, biomass burning, fossil fuel combustion, and expanding urbanization.

The spatial analyses further demonstrate considerable geographical disparities in pollution levels across Nigeria. Northern regions consistently recorded substantially higher $PM_{2.5}$ concentrations than southern regions, largely due to the combined effects of Harmattan dust transport, desertification, agricultural burning, and sparse vegetation cover. Conversely, southern Nigeria exhibited elevated concentrations of combustion-related pollutants, particularly NO_2 and CO, resulting from intensive industrialization, petroleum exploration, vehicular emissions, shipping activities, and high population density. Urban centres such as Lagos, Port Harcourt, Kano, Abuja, Kaduna, Onitsha, Aba, Ibadan, and Benin City remain persistent pollution hotspots because of rapid industrial expansion and increasing transportation demands.

The analysis also revealed pronounced seasonal variability, with the dry season consistently exhibiting significantly higher concentrations of particulate matter and gaseous pollutants than the wet season. Average national $PM_{2.5}$ concentrations during the dry season were approximately 61.7 ± 8.4 μg m^{-3} compared with 39.8 ± 6.2 μg m^{-3} during the rainy season. Similar seasonal increases were observed for NO_2 and CO. These findings indicate that meteorological conditions exert considerable influence on pollutant accumulation and dispersion throughout Nigeria. Reduced rainfall, lower atmospheric humidity, increased dust transport, atmospheric stability, and extensive biomass burning during the Harmattan season collectively contribute to severe deterioration in ambient air quality.

Summaries of major findings and respective environmental consequences are presented in Table 10.

The environmental implications of these findings are profound. Persistent increases in particulate matter imply that millions of

Nigerians continue to be exposed to concentrations substantially exceeding both national and World Health Organization air quality guidelines. Chronic exposure to elevated $PM_{2.5}$ has been associated with increased risks of asthma, chronic obstructive pulmonary disease, cardiovascular diseases, lung cancer, stroke, diabetes, adverse pregnancy outcomes, and premature mortality.

Table 10: Summary of Major Findings and Their Environmental Implications

Parameter	Principal Finding	Environmental Implication
$PM_{2.5}$	Strong increasing trend (2010–2024)	Persistent deterioration of air quality and increasing human exposure
NO_2	Significant upward trend	Increased emissions from traffic, industry, and power generation
O_3	Moderate increasing trend	Enhanced photochemical pollution associated with urbanization and climate change
CO	Slight decreasing trend	Partial improvement in combustion efficiency but localized hotspots remain
Seasonal variability	Higher pollution during dry season	Strong influence of Harmattan dust, biomass burning, and atmospheric stability
Spatial distribution	Northern Nigeria exhibits highest $PM_{2.5}$; southern industrial regions highest NO_2	Regional differences require location-specific mitigation strategies
Trend significance	$PM_{2.5}$, NO_2 and O_3 statistically significant ($p < 0.001$)	Demonstrates persistent long-term deterioration in national air quality

The simultaneous increase in nitrogen dioxide and ozone further compounds respiratory health risks through airway inflammation, oxidative stress, impaired pulmonary function, and increased susceptibility to respiratory infections.

The observed pollution trends also reflect broader environmental changes occurring across Nigeria. Rapid urbanization has significantly increased vehicular density, construction activities, energy consumption, and industrial emissions. Simultaneously, climate change has altered atmospheric conditions that influence pollutant transport, chemical transformation, and persistence. Rising temperatures and prolonged dry seasons favour enhanced ozone formation and increased dust mobilisation, while declining vegetation cover reduces the natural capacity of ecosystems to remove atmospheric pollutants. These interactions demonstrate that air pollution management cannot be separated from broader climate adaptation and sustainable urban development strategies.

The findings further highlight the importance of satellite remote sensing for environmental monitoring in countries where conventional monitoring networks remain inadequate. Nigeria currently possesses relatively few continuous ground-based air quality monitoring stations compared with its geographical size and population. Consequently, satellite-derived observations provide valuable nationwide information that enables assessment of pollution trends across regions where direct measurements are unavailable. The integration of satellite observations with available ground-based monitoring systems can substantially improve exposure assessment, pollution forecasting, and environmental policy evaluation.

Although satellite observations provide broad spatial coverage, future monitoring programmes should incorporate higher spatial resolution datasets and expand validation using ground-based observations. Continuous monitoring stations should be strategically established across all geopolitical zones, particularly within rapidly expanding urban centres, industrial corridors, mining regions, transportation hubs, agricultural zones, and areas frequently affected by biomass burning. Such integrated monitoring systems would improve the accuracy of pollution estimation while supporting real-time public health advisories.

Machine learning and artificial intelligence techniques also present significant opportunities for advancing national air quality monitoring. Hybrid models combining satellite observations, meteorological variables, land-use information, traffic density, industrial emissions, and socioeconomic indicators can substantially improve prediction accuracy for pollutant concentrations. These approaches would enable the development of high-resolution national pollution maps capable of identifying emerging hotspots and forecasting future pollution episodes. Such predictive systems are increasingly being adopted internationally and could strengthen Nigeria's environmental management capacity.

The results additionally underscore the necessity for stronger environmental governance. Existing emission regulations require improved enforcement alongside more comprehensive national emission inventories. Industrial facilities should adopt cleaner production technologies and emission control systems, while vehicular emission standards should be periodically updated to align with international best practices. Open waste burning, uncontrolled biomass combustion, and illegal industrial emissions require stricter regulation and continuous compliance monitoring. Furthermore, transitioning from diesel generators and traditional biomass fuels to renewable energy sources would substantially reduce emissions of particulate matter and nitrogen oxides.

Urban planning also has a critical role in reducing long-term pollution exposure. Expansion of public transportation systems, promotion of electric mobility, development of green infrastructure, protection of urban forests, and implementation of sustainable land-use policies can collectively reduce pollutant emissions while improving atmospheric dispersion. Establishing urban green belts and increasing tree cover would enhance natural pollutant removal through dry deposition and improve microclimatic conditions within densely populated cities.

Regional cooperation across West Africa is equally important because atmospheric pollutants frequently cross national boundaries. Harmattan dust originating from the Sahara Desert, biomass burning emissions from neighbouring countries, and transboundary transport of industrial pollutants contribute substantially to Nigeria's ambient pollution burden. Strengthening regional environmental agreements, sharing atmospheric monitoring data, and coordinating emission reduction initiatives would improve the effectiveness of pollution control throughout the region.

The findings of this study therefore provide an important scientific foundation for future environmental policy, public health planning, and sustainable development initiatives in Nigeria. The statistically significant increases in $PM_{2.5}$, NO_2, and O_3 indicate that without substantial intervention, ambient air quality is likely to continue deteriorating over the coming decades. Continued increases in urbanization, industrialization, transportation demand, and climate-related environmental changes may further intensify pollution unless comprehensive mitigation measures are implemented.

Overall, this nationwide satellite-based assessment demonstrates that ambient air pollution has become a persistent and expanding environmental challenge in Nigeria. The integration of long-term satellite observations with robust statistical analyses has provided comprehensive evidence of temporal trends, seasonal variability, and regional disparities in pollutant concentrations. These findings emphasize the urgent need for strengthened monitoring infrastructure, improved emission control policies, cleaner energy transitions, climate-resilient urban planning, and sustained environmental surveillance. Such interventions will be essential for achieving improved air quality, protecting ecosystem integrity, reducing future disease burdens, and advancing Nigeria's progress toward the Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

4. 0 Conclusion

This study provides a comprehensive satellite-based assessment of the long-term temporal trends, seasonal variability, spatial distribution, and statistical characteristics of major ambient air pollutants across Nigeria over the period 2010–2024. By integrating multi-source satellite observations with robust statistical analyses, including descriptive statistics, seasonal decomposition, Mann–Kendall trend analysis, Sen's slope estimation, and geospatial assessment, the study offers a nationwide perspective on the evolution of air quality under the influence of rapid urbanization, industrialization, population growth, changing land-use patterns, biomass burning, desertification, and climate variability.

The results demonstrate that Nigeria has experienced a persistent deterioration in ambient air quality during the fifteen-year study period. Fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ground-level ozone (O_3) exhibited statistically significant increasing trends, whereas carbon monoxide (CO) showed a slight but significant decline. Among all pollutants investigated, $PM_{2.5}$ recorded the most pronounced increase, with annual mean concentrations rising from approximately 43.2 μg m^{-3} in 2010 to 63.8 μg m^{-3} in 2024. Mann–Kendall trend analysis confirmed a highly significant upward trend ($p < 0.001$), while Sen's slope estimated an annual increase of approximately 1.37 μg m^{-3}. Nitrogen dioxide similarly showed a significant positive trend associated with expanding transportation activities, fossil-fuel combustion, industrial development, and increasing electricity generation. Ground-level ozone increased gradually throughout the study period, reflecting enhanced atmospheric photochemical reactions driven by increasing precursor emissions and changing meteorological conditions. Conversely, carbon monoxide exhibited a modest declining trend, suggesting gradual improvements in combustion efficiency and partial adoption of cleaner energy technologies, although localized urban hotspots remain a concern.

The spatial analysis revealed pronounced regional disparities in air pollution across Nigeria. Northern Nigeria consistently exhibited substantially higher $PM_{2.5}$ concentrations than southern Nigeria, largely due to Harmattan dust transport from the Sahara Desert, desertification, biomass burning, agricultural residue combustion, sparse vegetation cover, and prolonged dry-season atmospheric stability. In contrast, southern Nigeria recorded relatively higher concentrations of combustion-related pollutants, particularly NO_2 and CO, driven by petroleum exploration, industrial emissions, maritime activities, dense transportation networks, urbanization, and high population density. Industrial and commercial cities including Lagos, Port Harcourt, Abuja, Kano, Kaduna, Ibadan, Benin City, Onitsha, Aba, and Warri emerged as persistent pollution hotspots requiring priority intervention.

Seasonal analysis further demonstrated that atmospheric pollution in Nigeria follows a distinct seasonal cycle. Pollutant concentrations were consistently higher during the dry season than during the rainy season. $PM_{2.5}$ concentrations during the Harmattan period exceeded wet-season values by more than 50%, while NO_2 and CO also showed significant seasonal increases. These seasonal variations are strongly influenced by meteorological factors such as reduced rainfall, lower atmospheric humidity, enhanced dust transport, atmospheric inversion, biomass burning, and reduced wet deposition during the dry season. The seasonal decomposition analysis confirmed that seasonality constitutes one of the dominant drivers of pollutant variability across Nigeria.

The statistical trend analyses provided robust evidence that current emission control measures have not been sufficient to reverse the deterioration of ambient air quality. The consistent upward trajectories of $PM_{2.5}$, NO_2, and O_3 suggest that anthropogenic emission sources continue to increase despite existing environmental regulations. Rapid urban expansion, increasing motorization, industrial growth, widespread use of diesel-powered electricity generators, open waste burning, and dependence on biomass fuels continue to contribute substantially to atmospheric pollution. The findings further indicate that climate change may amplify pollution levels through increasing temperatures, altered atmospheric circulation, prolonged dry seasons, and enhanced photochemical formation of secondary pollutants.

The study also demonstrates the considerable value of satellite remote sensing for national air quality assessment in countries with limited ground-based monitoring infrastructure. Satellite-derived observations provide consistent spatial coverage across regions where continuous monitoring stations are unavailable, enabling comprehensive assessment of long-term pollution dynamics. The integration of remote sensing datasets with statistical modelling offers an effective framework for national environmental surveillance, exposure assessment, pollution forecasting, and evidence-based policymaking.

The implications of the observed pollution trends extend beyond environmental quality and have significant consequences for sustainable development, climate resilience, and public health. Persistent exposure to elevated $PM_{2.5}$, NO_2, and O_3 concentrations substantially increases the risk of respiratory diseases, cardiovascular disorders, chronic obstructive pulmonary disease, asthma, lung cancer, adverse pregnancy outcomes, metabolic diseases, and premature mortality. Although this study primarily focused on pollutant dynamics, the documented deterioration in air quality underscores the urgent need for coordinated interventions aimed at minimizing population exposure, particularly among children, older adults, and individuals with pre-existing respiratory conditions.

The findings emphasize the necessity for substantial improvements in Nigeria's environmental management framework. Expansion of nationwide ground-based monitoring stations should complement satellite observations to improve the accuracy of pollutant estimation and facilitate continuous validation. Stronger enforcement of industrial emission standards, modernization of vehicular emission regulations, improved traffic management, elimination of open waste burning, promotion of cleaner household energy technologies, and accelerated transition toward renewable energy sources represent critical strategies for reducing ambient pollution. Sustainable urban planning incorporating green infrastructure, improved public transportation, urban afforestation, and low-emission development pathways will also contribute significantly to long-term air quality improvement.

Furthermore, future research should integrate satellite-derived pollution estimates with high-resolution ground observations, meteorological variables, land-use characteristics, demographic information, and health surveillance databases. Such multidisciplinary approaches would improve understanding of pollutant exposure pathways, facilitate more accurate estimation of disease burden, and support the development of predictive models for environmental health risk assessment. The application of artificial intelligence and machine learning algorithms also offers considerable potential for enhancing pollution forecasting and identifying emerging hotspots across Nigeria.

Overall, this study provides one of the most comprehensive national evaluations of long-term ambient air quality trends in Nigeria using satellite-derived observations. The evidence generated demonstrates that particulate matter pollution remains the dominant environmental challenge, while increasing nitrogen dioxide and ozone concentrations indicate worsening anthropogenic emissions and atmospheric photochemical activity. The documented temporal and spatial patterns provide an important scientific foundation for future environmental policy formulation, air quality management, climate adaptation strategies, and public health planning. Addressing Nigeria's growing air pollution problem will require sustained investment in environmental monitoring infrastructure, stronger regulatory enforcement, cleaner technologies, integrated urban planning, regional cooperation, and evidence-based policy interventions. Such measures are essential not only for improving ambient air quality but also for safeguarding public health, protecting ecosystem integrity, reducing environmental inequalities, and supporting Nigeria's progress toward the achievement of the Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

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Declaration

Ethics Approval and Consent to Participate

Not applicable

Consent for Publication

All authors have read and approved the final version of the manuscript and consented to its publication.

Availability of Data and Materials

Data shall be made available upon request

Funding

The work was funded by the Tertiary Education Trust Fund of Nigeria

Competing Interests

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

Author Contributions

Ifiok Dominic Uffia conceived and designed the study, performed the analyses, and drafted the manuscript. Ofonimeh Emmanuel Udofia contributed to data collection, statistical analysis, and manuscript revision. Utibe Evans Bassey interpreted the results, reviewed the literature, and critically revised the manuscript. Godswill Emmanuel John supervised the study, validated the findings, and approved the final manuscript.

Cite as: Uffia, I. D., Udofia, O. E., Bassey, U. E., & John, G. E. (2026). Long-term temporal trends and seasonal variability of ambient air pollutants in Nigeria: A satellite-based assessment (2010–2024). *Journal of Natural and Artificial Scientific Systems, 3*(2), 169–200. https://doi.org/10.5281/zenodo.21263306