

## MONITORING CARBON MONOXIDE AND AEROSOL CONCENTRATIONS IN ABA METROPOLIS, ABIA STATE, NIGERIA: 2019–2024 TRENDS

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**Background:** Air pollution poses major health and environmental risks globally, with disproportionate impacts in low- and middle-income countries lacking robust monitoring systems. In Nigeria, rapid urbanization, fossil fuel dependence, and informal industrial activities have intensified urban air quality challenges. In Aba, limited continuous, pollutant-specific monitoring has constrained comprehensive understanding of long-term temporal and spatial pollution dynamics. **Objectives:** This study quantified tropospheric carbon monoxide (CO) and aerosol concentrations in Aba (2019–2024), identified seasonal trends and spatial hotspots, and assessed inter-annual variability using Sentinel-5 Precursor (Sentinel-5P) satellite data integrated with GIS-based spatial analysis. **Methods:** Satellite-derived CO and aerosol data for Aba were obtained from Sentinel-5P (2019–2024). Datasets were accessed and processed within Google Earth Engine (GEE), where CO and aerosol bands were filtered by date and spatially constrained to the metropolitan boundary. Monthly and annual means were computed using custom JavaScript. Processed rasters were exported as GeoTIFF files and analysed in ArcGIS 10.7.1 to generate spatial distribution maps and classify concentration levels. Descriptive statistics and paired-sample t-tests were performed to evaluate inter-annual variability. Time-series analyses were used to assess seasonal trends and temporal fluctuations across the study period. **Results:** CO and aerosol levels exhibited pronounced seasonal peaks, consistently highest in February, and inter-annual fluctuations linked to post-pandemic recovery and energy use patterns. Central commercial and industrial areas consistently emerged as pollution hotspots, while peripheral zones recorded lower concentrations. Both pollutants responded to anthropogenic activity and policy changes, such as fuel subsidy removal, and their accumulation was modulated by seasonal climatic factors. Aerosols showed more persistent atmospheric presence than CO. This multi-year, high-resolution assessment provides a pollutant-specific baseline, filling gaps left by short-term ground-based studies and enabling evidence-based urban air quality management in mid-sized cities. **Conclusion:** This study quantified temporal and spatial dynamics of CO and aerosol concentrations in Aba (2019–2024) using Sentinel-5P and GIS analysis, revealing seasonal peaks, urban pollution hotspots, policy-sensitive variations, and providing a high-resolution baseline addressing gaps in continuous, pollutant-specific monitoring.

**Keywords:** air quality; urban air pollution; carbon monoxide (CO); aerosol optical depth (AOD); Sentinel-5P; remote sensing; Google Earth Engine; spatiotemporal analysis; pollution hotspots.

### INTRODUCTION

Rising environmental pollution is increasingly recognized as a critical threat to human health, economic productivity, and sustainable development worldwide (Manisalidis et al., 2020; Gul & Das, 2023). Atmospheric pollution alone is associated with over seven million premature deaths annually (Manisalidis et al., 2020; Gul & Das, 2023; WHO, 2024), with the burden disproportionately affecting low- and middle-income countries due to limited mitigation capacity. Beyond human health, air pollution disrupts ecosystems, reduces biodiversity, and undermines climate stability (Lovett et al., 2009; Ghorani-Azam et al., 2016; Izah et al., 2023). Contributing sources include vehicular emissions, industrial activities, biomass burning, and natural phenomena such as dust storms and wildfires (IARC, 2016). While developed countries have mitigated these impacts through stringent regulations and advanced monitoring technologies (Ross et al., 2012), many rapidly urbanizing economies continue to experience hazardous air quality levels (Mathew et al., 2024).

Across Africa, rapid population growth, urban expansion, and extensive reliance on biomass fuels have created complex air quality challenges (Abera et al., 2021; Petkova et al., 2013; Jiying et al., 2023; Atuyambe et al., 2024). Despite growing concerns, many Africa countries lack comprehensive air quality monitoring networks, particularly for continuous, pollutant-specific data (Abera et al., 2021; Petkova et al., 2013). In Nigeria, heavy fossil fuel use, informal industrial growth, and weak regulatory enforcement have produced urban pollution

hotspots with significant public health implications (Ladan, 2013; Abaje et al., 2020; Awofeso, 2011; Obanya et al., 2018; Fakinle et al., 2020). Major cities including Lagos, Port Harcourt, Abuja, and Kano experience high CO and aerosol concentrations linked to traffic congestion, diesel generators, and industrial emissions (Adeyanju & Manohar, 2017; Merem et al., 2018; Amaechi et al., 2024a; Lala et al., 2025), contributing to respiratory and cardiovascular diseases (Amaechi et al., 2023a; Sadiq et al., 2022).

Aba, a major commercial and manufacturing hub in southeastern Nigeria, experiences significant environmental pressures from high vehicular density, diesel generator use, informal industrial activity, and frequent waste burning (Akuagwu & Ozeh, 2013; Nwosu & Ewurum, 2018; Okey-Wokeh et al., 2020). These activities have resulted in substantial air quality deterioration. However, continuous, high-resolution monitoring is largely absent, limiting comprehensive understanding of temporal and spatial pollution dynamics and their health implications (Akuagwu & Ozeh, 2013; Nwosu & Ewurum, 2018).

Previous studies in Aba have largely relied on ground-based monitoring. Agwu & Ozeh (2013) employed electrochemical gas sensors and gravimetric techniques at six locations, revealing frequent exceedances of WHO CO and SO<sub>2</sub> standards. Similarly, Anietimfon & Anaekwe (2015) measured SO<sub>2</sub> using the West-Gaeke method, and Nwosu & Ewurum (2018) assessed air quality near the Enyimba dumpsite using portable gas detectors and gravimetric samplers, identifying elevated CO, H<sub>2</sub>S, CH<sub>4</sub>,

and PM concentrations. More recently, Diagi et al. (2025) focused on CO and particulate matter using handheld sensors across different urban land uses. Although these studies demonstrate the severity of pollution, their localized and short-term approaches limit comprehensive temporal and spatial analyses. Abulude et al. (2023) applied satellite-derived data from Plume Labs for broader regional assessment, but reliance on generalized air quality indices and a short 60-day observation period restricted pollutant-specific and long-term trend analysis.

Satellite-based remote sensing provides a scalable and cost-effective approach to overcome these limitations. The European Space Agency's Sentinel-5P satellite, equipped with the Tropospheric Monitoring Instrument (TROPOMI), delivers near-daily, high-resolution data on key atmospheric pollutants, including CO and aerosols (Mathew et al., 2024; Enuneku et al., 2025; Okoduwa & Amaechi, 2023).

Therefore, the present study aims to quantify tropospheric CO and aerosol concentrations across Aba metropolis using Sentinel-5P data and GIS-based spatial analysis. Specifically, study seeks to:

- 1) determine temporal trends and seasonal variations of CO and aerosols from 2019 to 2024;
- 2) identify spatial hotspots of elevated pollutant concentrations within the city;
- 3) assess inter-annual variability.

The working hypothesis is that CO and aerosol concentrations are highest in densely populated commercial and industrial zones, and that temporal patterns reflect seasonal variations in combustion activities. By integrating satellite-based observations with GIS analysis, this study addresses the current gap in continuous, pollutant-specific monitoring in Aba, providing a foundation for informed urban air quality management.

## MATERIALS AND METHODS

### Study area

Aba Metropolis, located in Abia State, south-eastern Nigeria (Figure 1), is a major commercial and industrial hub

(Abaje et al., 2020; Ajayi et al., 2024). The city comprises Aba North and Aba South Local Government Areas, covering approximately 72 km<sup>2</sup>, and lies between latitudes 5°04'–5°08'N and longitudes 7°20'–7°25'E (Okey-Wokeh et al., 2020; Tanko et al., 2022). Aba South hosts the central business district, whereas Aba North primarily consists of residential and peripheral commercial zones. The city's strategic location connects it to major trade centres including Umuahia, Owerri, Port Harcourt, and Ikot Ekpene, resulting in high vehicular traffic and intensive industrial activity (Akuagwu et al., 2016; Kanu et al., 2023).

With a population exceeding one million, rapid urban expansion has caused congestion, inadequate infrastructure, and rising air pollution (Okey-Wokeh et al., 2020; Tanko et al., 2022). Aba is often referred to as the "Japan of Africa" due to its thriving small- and medium-scale industries in textiles, leatherwork, plastics, metal fabrication, and brewing (Abaje et al., 2020; Ajayi et al., 2024). While these industries drive local livelihoods, they also emit pollutants such as CO, NO<sub>2</sub>, SO<sub>2</sub>, volatile organic compounds (VOCs), and aerosols, contributing to deteriorating air quality (Nwogu & Umezuruike, 2018; Abulude et al., 2023).

The city experiences a tropical rainforest climate, characterized by high humidity and a bimodal rainfall pattern, with annual precipitation ranging from 1,800 to 2,400 mm and peak rainfall occurring between June and September (NIMET, 2022). Temperatures typically range from 26°C to 32°C. These climatic conditions influence pollutant dispersion, often facilitating the accumulation of CO and aerosols under stagnant atmospheric conditions (Nwogu & Umezuruike, 2018; Abulude et al., 2023). Aba's predominantly flat to gently undulating topography, with elevations of 50–75 m above sea level, further restricts air circulation. The Aba River, a tributary of the Imo River, suffers from poor drainage and waste disposal, exacerbating pollution during flood events (Awuchi et al., 2023; Okolo et al., 2025; Kanu et al., 2023).

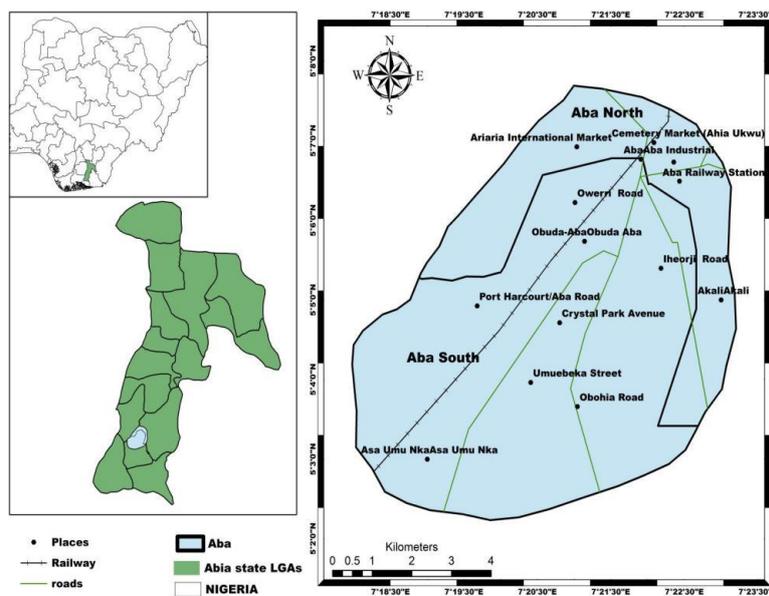


Figure 1. Map of Aba

### Data source and collection

CO and aerosol concentrations in Aba were analysed using secondary satellite data from the Sentinel-5P. Sentinel-5P, launched in October 2017 under the European Space Agency's

Copernicus Programme, is equipped with the Tropospheric Monitoring Instrument (TROPOMI), which is capable of detecting a wide range of atmospheric pollutants including CO and aerosols. TROPOMI captures data across ultraviolet, visible, near-infrared, and short-wave infrared bands, which enables the

satellite to measure key atmospheric parameters with high precision. Its spatial resolution of  $3.5 \times 7 \text{ km}^2$  and daily global coverage make it suitable for identifying pollution hotspots and observing seasonal fluctuations (Omrani et al., 2020).

### Data processing and analysis

Data processing involved the following steps.

**Data extraction** – Data extraction and processing were performed using GEE, a cloud-based platform for the management, processing, and visualization of geospatial datasets, including Sentinel-5P products (Amaechi et al., 2023b; Amaechi et al., 2024b).

**CO and aerosol optical depth (AOD)** was extracted using JavaScript. The prepared Sentinel-5P datasets were filtered according to pollutant type, temporal coverage (2019–2024), and the geographic boundaries of Aba.

**Temporal aggregation** – Daily data were aggregated to monthly and annual averages to analyse seasonal and interannual variations.

**Spatial mapping** – The data were projected onto the geographic boundaries of Aba using GIS tools to identify local pollution hotspots.

This methodology ensures reproducibility by clearly specifying data sources and aggregation procedures (Omrani et al., 2020).

### Method of analysis

A systematic workflow (Figure 2) was implemented to assess spatial and temporal variations of CO and aerosol concentrations in Aba Metropolis. The methodology integrates geospatial processing with statistical analysis, and consists of the following steps.

**Data Selection and Filtering** – Sentinel-5P datasets were accessed from the GEE data catalogue. CO and aerosol optical

depth (AOD) data for the period 2019–2024 were selected to ensure consistency and completeness. Datasets were filtered spatially to include only the Aba metropolitan area and temporally to extract relevant daily measurements.

**Data Extraction in GEE** – Custom scripts in GEE's JavaScript environment were developed to extract CO and aerosol bands, apply date filters, and calculate monthly and annual averages. CO measurements are expressed in  $\text{mol/m}^2$ , while aerosol data are unitless. The baseline date of January 1, 2019, was used to ensure uniform coverage across all parameters.

**Raster Export and GIS Integration** – Processed raster datasets were exported from GEE as GeoTIFF files, preserving spatial resolution and georeferencing. These files were imported into ArcGIS 10.7.1 for spatial visualization and analysis. Pollutant concentrations were classified into three categories: high, moderate, and low, with a red–yellow–green colour scheme to identify pollution hotspots.

**Statistical Analysis** – Monthly and annual averages were computed, and descriptive statistics (mean and standard deviation) were calculated to summarize trends. A paired-sample t-test was applied to evaluate the significance of differences in pollutant concentrations between consecutive years, accounting for interrelated temporal trends.

**Visualization** – Time-series plots and charts were generated to illustrate temporal dynamics of CO and aerosol concentrations, facilitating interpretation of seasonal and interannual variations.

CO and aerosols were selected due to their direct association with major emission sources in Aba, including vehicular traffic, industrial activities, and waste combustion (Akuagwu & Ozeh, 2013; Nwosu & Ewurum, 2018). These pollutants are recognized by international air quality frameworks as reliable indicators of urban pollution. The dataset characteristics are summarized in Table 1.

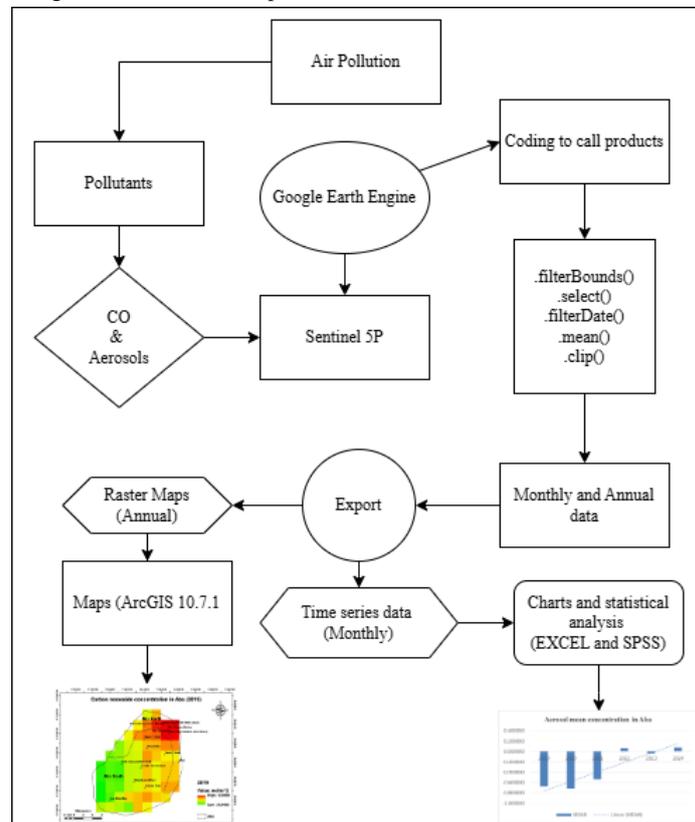


Figure 2. Schematic illustration of the research design

Table 1. CO and aerosols dataset obtained from Sentinel-5P

Band Name	Dataset	Unit	Min	Max	Description
CO_column_number_density	OFFL/L3_CO	mol/m <sup>2</sup>	-34.43	5.71	Vertically integrated CO column density
absorbing_aerosols_index	OFFL/L3_AER_AI	-	-21	39	A measure of the prevalence of aerosols in the atmosphere

## RESULTS

### CO results

Annual CO concentrations in Aba from 2019 to 2024 are summarized in Table 2. In 2019, CO levels were relatively low and stable, with a mean of 0.0504 mol/m<sup>2</sup> (range: 0.0499–0.0509 mol/m<sup>2</sup>; SD = 0.0002). In 2020, the mean concentration increased slightly to 0.0553 mol/m<sup>2</sup> (range: 0.0548–0.0557 mol/m<sup>2</sup>; SD = 0.0002). A mild decrease was observed in 2021 (mean = 0.0532 mol/m<sup>2</sup>; range: 0.0525–0.0535 mol/m<sup>2</sup>; SD = 0.0002), followed by a small rise in 2022 (mean = 0.0505 mol/m<sup>2</sup>; range: 0.0497–0.0511 mol/m<sup>2</sup>; SD = 0.0003). The lowest annual mean was recorded in 2023 (0.0496 mol/m<sup>2</sup>; range: 0.0489–

0.0501 mol/m<sup>2</sup>; SD = 0.0002), with a subsequent increase in 2024 to the highest mean of 0.0558 mol/m<sup>2</sup> (range: 0.0548–0.0562 mol/m<sup>2</sup>; SD = 0.0003) (Table 2).

Monthly CO concentrations (Table 3) exhibited clear seasonal patterns throughout the study period. In all years, February consistently recorded the highest concentrations, ranging from 0.065 mol/m<sup>2</sup> in 2023 to 0.080 mol/m<sup>2</sup> in 2020, while October showed the lowest values, ranging from 0.034 mol/m<sup>2</sup> in 2022 to 0.042 mol/m<sup>2</sup> in 2024. Other months displayed moderate variability, with minor fluctuations in the mid-year period. These results indicate a recurring seasonal trend, with early-year peaks and late-year minima, consistent across the six-year dataset.

Table 2. Annual CO concentrations (mol/m<sup>2</sup>) in Aba, 2019–2024

Year	Minimum	Maximum	Mean	SD
2019	0.0499	0.0509	0.0504	0.0002
2020	0.0548	0.0557	0.0553	0.0002
2021	0.0525	0.0535	0.0532	0.0002
2022	0.0497	0.0511	0.0505	0.0003
2023	0.0489	0.0501	0.0496	0.0002
2024	0.0548	0.0562	0.0558	0.0003

Table 3. Monthly CO concentrations (mol/m<sup>2</sup>) in Aba, 2019–2024

Month	2019	2020	2021	2022	2023	2024
Jan	0.068	0.067	0.064	0.065	0.064	0.067
Feb	0.071	0.080	0.071	0.068	0.065	0.073
Mar	0.058	0.067	0.060	0.061	0.053	0.063
Apr	0.048	0.050	0.050	0.046	0.046	0.047
May	0.040	0.044	0.040	0.039	0.040	0.047
Jun	0.044	0.043	0.043	0.039	0.039	0.046
Jul	0.046	0.044	0.051	0.048	0.044	0.054
Aug	0.045	0.049	0.050	0.051	0.050	0.060
Sep	0.038	0.044	0.042	0.041	0.039	0.045
Oct	0.037	0.036	0.039	0.034	0.037	0.042
Nov	0.042	0.051	0.046	0.046	0.046	0.050
Dec	0.056	0.059	0.059	0.058	0.056	0.061

### CO spatial distribution

The spatial distribution of CO concentrations in Aba from 2019 to 2024 is presented in Figures 3–8. In 2019, high CO levels (up to 0.0509 mol/m<sup>2</sup>) were observed in the central and northern commercial and industrial zones, including Aba Industrial area, Ariaria International Market, Aba Railway Station, Cemetery Market, Ngwa Road Market, and Owerri Road. Moderate

concentrations were recorded in central residential areas, while peripheral southern regions exhibited the lowest values (approximately 0.0499 mol/m<sup>2</sup>).

In 2020, high CO concentrations increased slightly to 0.0557 mol/m<sup>2</sup> in the previously noted central and northern areas, whereas the central region of Aba South showed comparatively lower concentrations (0.0548 mol/m<sup>2</sup>). The

pattern persisted in 2021, with central and northern zones remaining in the high concentration category (approximately  $0.0535 \text{ mol/m}^2$ ), while southern peripheral areas registered lower concentrations (approximately  $0.0525 \text{ mol/m}^2$ ).

By 2022, the highest concentrations ( $0.0511 \text{ mol/m}^2$ ) shifted toward the eastern parts of Aba North and South, including key commercial and transport corridors, while southwestern peripheral areas showed the lowest concentrations ( $0.0497 \text{ mol/m}^2$ ). In 2023, high CO concentrations (approximately  $0.0501 \text{ mol/m}^2$ )

remained in central commercial and industrial areas, with moderate levels in surrounding central zones and low concentrations in peripheral southern areas approximately  $0.0489 \text{ mol/m}^2$ .

In 2024, nearly all regions in Aba North and South recorded high to moderate CO concentrations, reaching a maximum of  $0.0562 \text{ mol/m}^2$ , whereas the southern periphery of Aba South maintained the lowest levels ( $0.0548 \text{ mol/m}^2$ ).

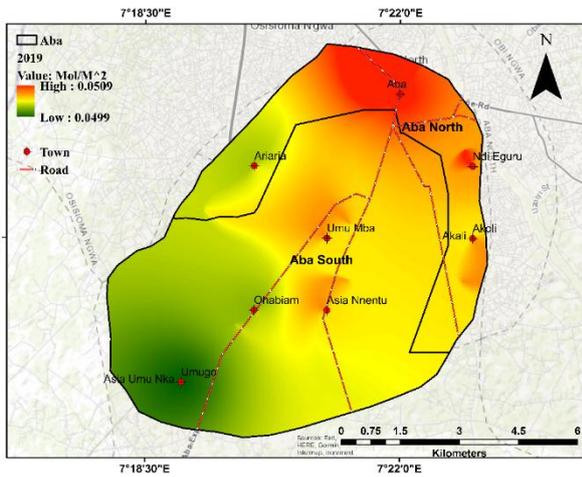


Figure 3. Map showing CO concentration in Aba for 2019

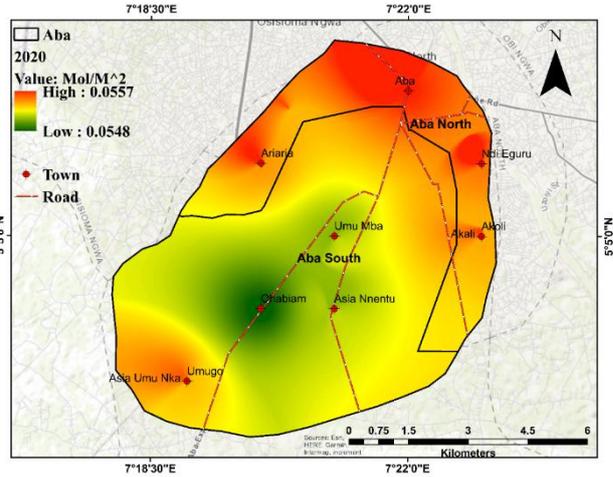


Figure 4. Map showing CO concentration in Aba for 2020

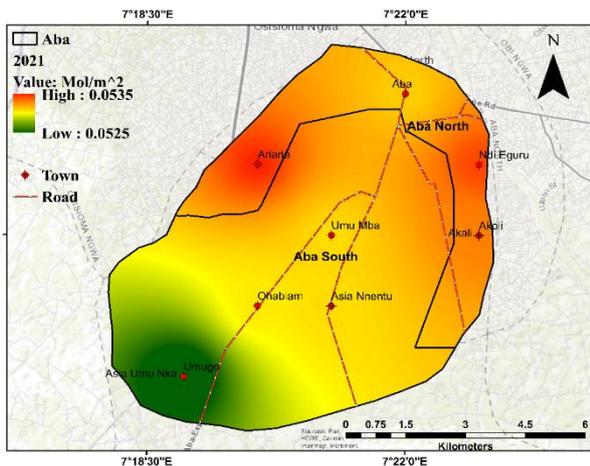


Figure 5. Map showing CO concentration in Aba for 2021

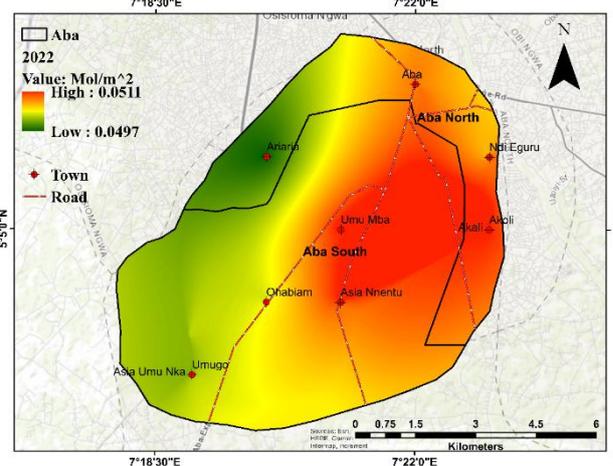


Figure 6. Map showing CO concentration in Aba for 2022

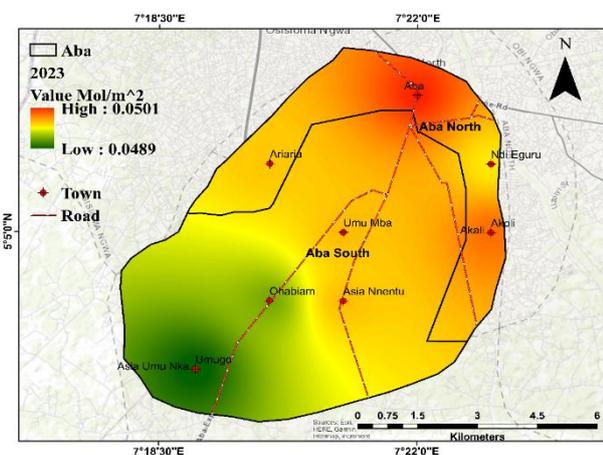


Figure 7. Map showing CO concentration in Aba for 2023

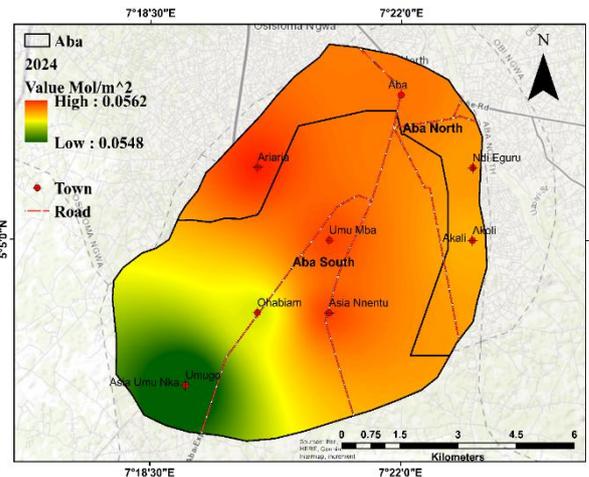


Figure 8. Map showing CO concentration in Aba for 2024

Annual spatial trends of CO concentrations (Figure 9) indicate a general stability in 2019, a peak in 2020, a slight decline in 2021, a modest rise in 2022, a minimum in 2023, and an

increase in 2024. These patterns reflect temporal shifts in concentration levels across central, northern, and peripheral areas of Aba.

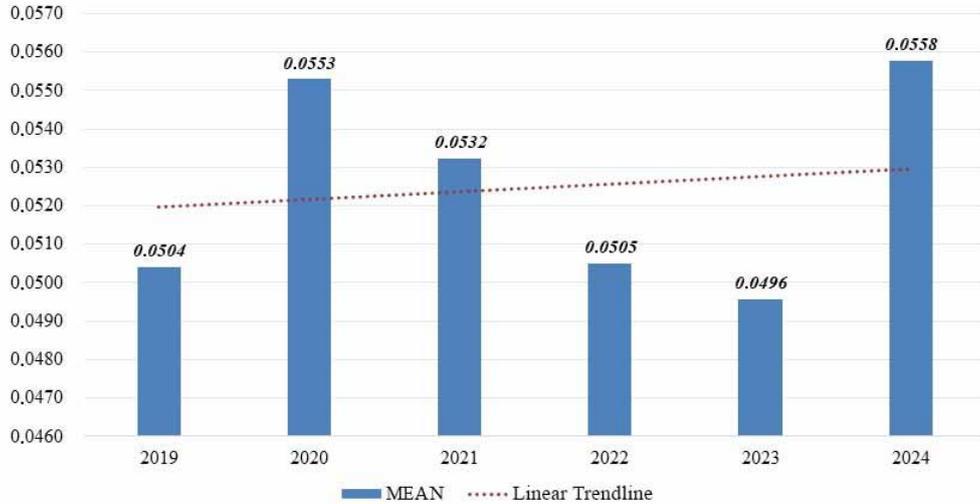


Figure 9. Trend of annual concentration of CO in Aba (2019–2024)

### Aerosol results

Annual aerosol values in Aba from 2019 to 2024 are summarized in Table 4. In 2019, mean aerosol concentrations were relatively low (mean = -0.6752; range: -0.7515 to -0.5835; SD = 0.0502). In 2020, the mean decreased slightly to -0.7115 (range: -0.7938 to -0.6427; SD = 0.0421), followed by a noticeable increase in 2021 (mean = -0.5316; range: -0.6080 to -0.4411; SD = 0.0485). In 2022, aerosol concentrations became positive (mean = 0.0637; range: 0.0126–0.1088; SD = 0.0306), reflecting an upward shift. A decline occurred in 2023 (mean = -0.0335; range: -0.0996 to

0.0533; SD = 0.0439), followed by stabilization in 2024 with the highest observed maximum (mean = 0.0792; range: 0.0011–0.1683; SD = 0.0509).

Monthly aerosol concentrations (Table 5) displayed consistent seasonal patterns. February consistently exhibited the highest concentrations across all years (0.330 to 1.496), while the wet season months, primarily May, June, and October, recorded the lowest values (-1.398 to -0.381). This indicates recurring intra-annual variability, with peak aerosol levels in the early months and minima during the mid- to late-year wet season.

Table 4. Annual minimum, maximum, mean and standard deviation of aerosol concentration from 2019–2024

Aerosol	2019	2020	2021	2022	2023	2024
Minimum	-0.7515	-0.7938	-0.6080	0.0126	-0.0996	0.0011
Maximum	-0.5835	-0.6427	-0.4411	0.1088	0.0533	0.1683
Mean	-0.6752	-0.7115	-0.5316	0.0637	-0.0335	0.0792
Standard deviation	0.0502	0.0421	0.0485	0.0306	0.0439	0.0509

Table 5. Monthly concentration of aerosol from 2019–2024

Month	2019	2020	2021	2022	2023	2024
Jan	0.214	1.26	-0.235	0.909	1.131	1.26
Feb	0.33	1.268	0.105	1.434	1.496	1.268
Mar	-0.143	0.381	-0.458	0.81	-0.132	0.381
Apr	-0.668	-0.002	-1.105	-0.115	-0.074	-0.002
May	-1.029	-0.349	-1.395	-0.386	-0.359	-0.349
Jun	-0.913	-0.381	-1.398	-0.526	-0.632	-0.381
Jul	-0.971	-0.242	-0.435	-0.517	-0.661	-0.242
Aug	-0.916	0.112	-0.588	-0.159	-0.251	0.112
Sep	-1.132	-0.606	-0.681	-0.489	-0.58	-0.606
Oct	-1.36	-0.799	-0.759	-0.632	-0.648	-0.799
Nov	-1.11	-0.323	-0.31	-0.05	-0.498	-0.323
Dec	-0.37	0.663	0.9	0.608	0.794	0.663

The spatial distribution of aerosols (Figures 10–15) revealed persistent high concentrations in central commercial and industrial areas, including Aba Industrial area, Ariaria International Market, Aba Railway Station, Cemetery Market, Ngwa Road Market, Owerri Road, Akali, and Obuda–Aba. Peripheral and southern regions generally recorded lower concentrations throughout the study period. Over the six-year period, high-concentration zones shifted slightly between northern, central, and eastern sections, while low-concentration

areas remained predominantly in the southern periphery of Aba South.

The annual trend (Figure 16) demonstrates an initial low and stable aerosol presence in 2019–2020, a pronounced increase in 2021–2022, a decline in 2023, and a subsequent stabilization in 2024. This reflects temporal variability across both the study area and the study period, with consistent spatial patterns in central, industrial, and peripheral zones.

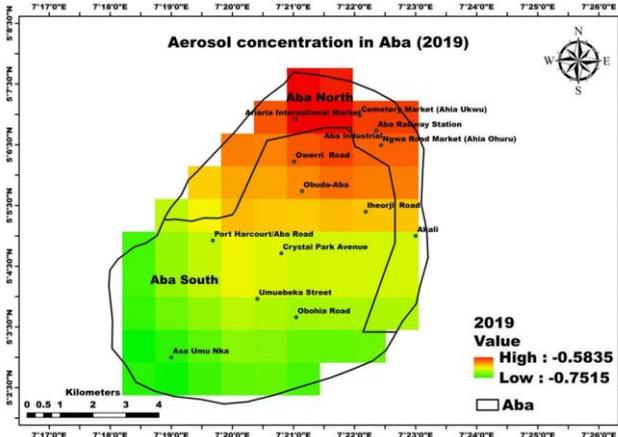


Figure 10. Map showing Aerosol concentration in Aba for 2019

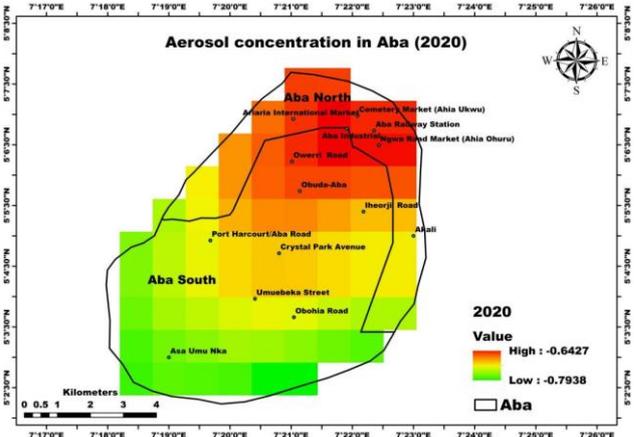


Figure 11. Map showing Aerosol concentration in Aba for 2020

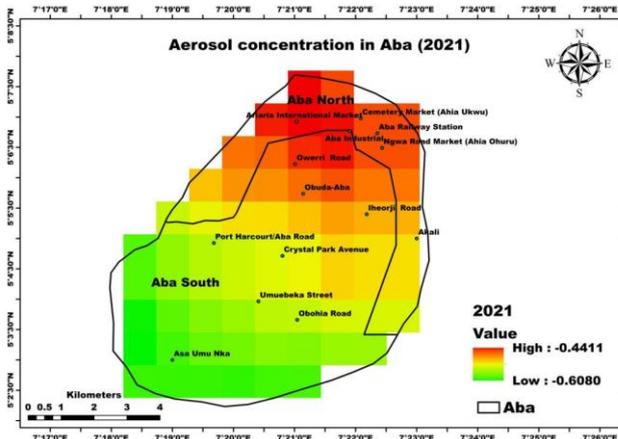


Figure 12. Map showing Aerosol concentration in Aba for 2021

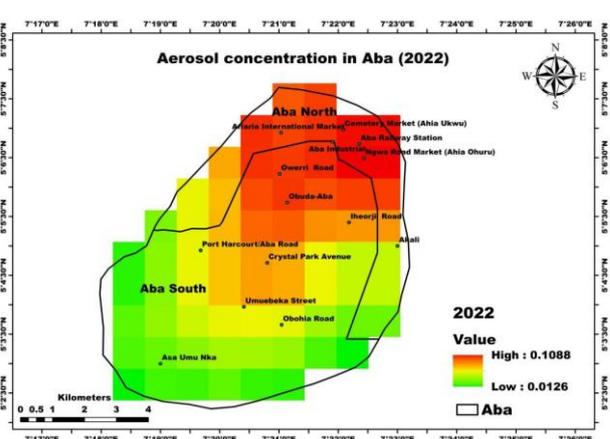


Figure 13. Map showing Aerosol concentration in Aba for 2022

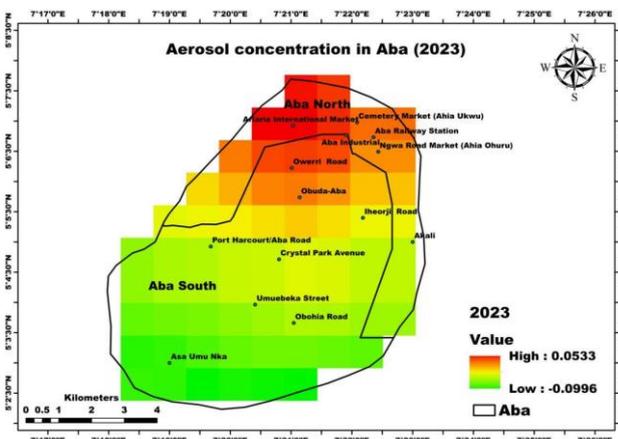


Figure 14. Map showing Aerosol concentration in Aba for 2023

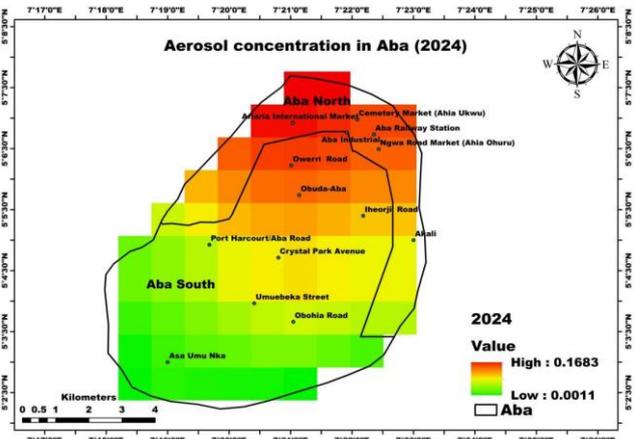


Figure 15. Map showing Aerosol concentration in Aba for 2024

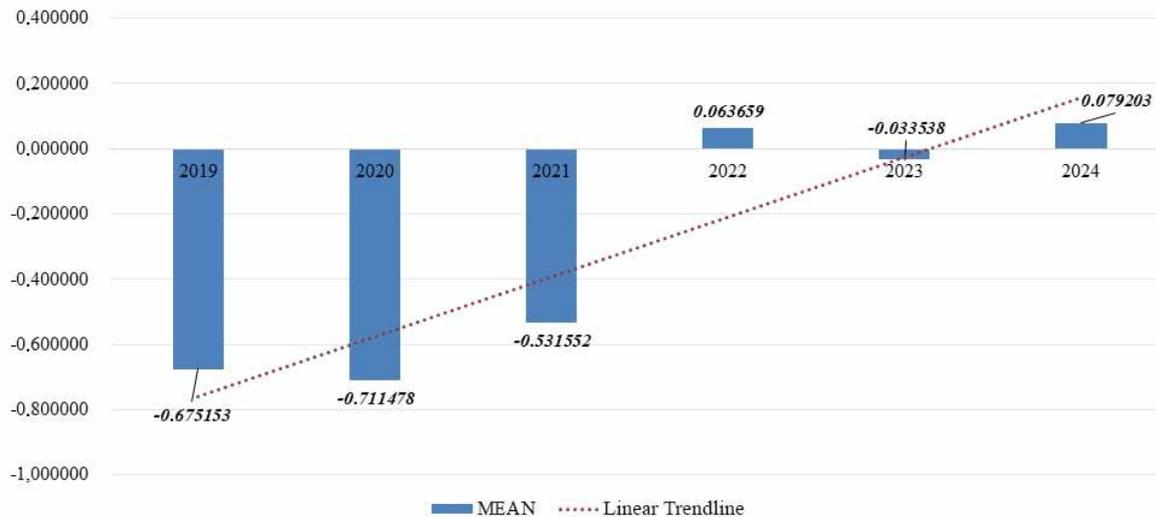


Figure 16. Trend of annual concentration of aerosol in Aba (2019–2024)

### Statistical analysis of year-to-year differences

The paired-sample t-test was applied to assess annual differences in CO and aerosol concentrations from 2019 to 2024 (Table 6).

For CO, statistically significant differences were observed between 2019–2020 ( $p = 0.016$ ), 2021–2022 ( $p = 0.027$ ), and 2023–2024 ( $p = 0.001$ ). No significant differences were found for 2020–2021 ( $p = 0.238$ ) and 2022–2023 ( $p = 0.105$ ). A direct comparison between 2019 and 2024 indicated a highly significant difference ( $p = 0.001$ ).

For aerosols, significant year-to-year differences were detected between 2019–2020 ( $p = 0.001$ ), 2020–2021 ( $p = 0.004$ ), and 2021–2022 ( $p = 0.003$ ). No significant differences were observed for 2022–2023 ( $p = 0.257$ ) and 2023–2024 ( $p = 0.117$ ). The comparison of 2019 and 2024 also revealed a highly significant difference ( $p = 0.002$ ).

These results indicate that both CO and aerosol concentrations exhibited significant interannual variability, with some periods of stability reflected by non-significant differences.

Table 6. Paired-sample t-test results for annual CO and aerosol concentrations

Parameters	2019 & 2020	2020 & 2021	2021 & 2022	2022 & 2023	2023 & 2024	2019 & 2024
CO	$p < 0.05$ (0.016)	$p > 0.05$ (0.238)	$p < 0.05$ (0.027)	$p > 0.05$ (0.105)	$p < 0.01$ (0.001)	$p < 0.01$ (0.001)
Aerosol	$p < 0.01$ (0.001)	$p < 0.05$ (0.004)	$p < 0.01$ (0.003)	$p > 0.05$ (0.257)	$p > 0.05$ (0.117)	$p < 0.01$ (0.002)

Note:  $p < 0.01$  – high significant difference;  $p < 0.05$  – significantly difference;  $p > 0.05$  – no significant difference (Okoduwa & Amaechi, 2023a)

## DISCUSSION

This study examined the temporal and spatial patterns of CO and aerosol concentrations in Aba from 2019 to 2024, highlighting the interplay between urban activity, seasonal climate, and national economic policies.

### Carbon monoxide

Annual CO concentrations exhibited a fluctuating trend. Levels were relatively low in 2019, increased in 2020 despite COVID-19 restrictions, decreased slightly in 2021–2022, reached a minimum in 2023, and rose again in 2024. The 2020 increase, despite limited movement, suggests substantial contributions from localized sources such as diesel generators, household combustion, and clustered industrial emissions. These findings are consistent with observations in other Nigerian cities, where informal energy sources maintained pollutant loads during lockdown periods (Okoduwa & Amaechi, 2023; Amaechi et al., 2025a; Amaechi et al., 2025b). The decline in 2023 coincides with Nigeria's fuel subsidy removal, reflecting reduced fuel consumption, whereas the 2024 rise reflects renewed mobility and economic activity, paralleling post-pandemic rebounds observed in cities such as Lagos, Port Harcourt, Jakarta, Mexico City, and New Delhi (Anugerah et al., 2021; Vega et al., 2021; Nigam et al., 2022; Mahato & Pal, 2022).

Monthly data reveal consistent seasonal variability, with February exhibiting the highest CO concentrations and October the lowest. Peak dry-season levels align with periods of low precipitation and increased combustion activity, whereas wet-season reductions are consistent with pollutant removal via rainfall and high humidity. Similar seasonal trends have been reported across West African and Southeast Asian cities, indicating that meteorology interacts with anthropogenic activity to modulate urban CO concentrations (Pochanart et al., 2003; Djossou et al., 2018; Oanh et al., 2023).

Spatially, CO concentrations were higher in central and northern commercial and industrial areas of Aba and lower in peripheral southern regions. This distribution reflects land use, traffic density, and population concentration. Comparable spatial disparities have been observed globally, where dense urban cores consistently show elevated CO levels relative to peri-urban zones (Imam & Banerjee, 2016; Wilson et al., 2015; Mutono et al., 2022).

### Aerosols

Aerosol concentrations exhibited a more complex trajectory. Between 2019 and 2021, negative values indicated low atmospheric particulate loads. From 2022 onwards, mean values became positive, with a slight dip in 2023 followed by a

peak in 2024. These trends mirror CO dynamics in response to economic activity and fuel consumption, with post-pandemic reopening contributing to higher concentrations. The interannual fluctuations also reflect localized combustion, dust resuspension, and open burning, consistent with patterns observed in other West African and Latin American urban centres (Amaechi et al., 2025a; Amaechi et al., 2025b; Amaechi et al., 2025c; Martínez Burgos et al., 2023; Mendez-Espinosa et al., 2020; Toro Araya et al., 2021).

Seasonally, aerosol levels peaked in February and were lowest during wet months such as May, June, and October, reflecting the influence of rainfall on particulate removal. This seasonal cycle aligns with observations from Accra, Bangkok, Hanoi, and Southern Hemisphere cities like Bogotá and Santiago, where dry and stagnant periods favour accumulation while precipitation facilitates dispersion (Fosu-Amankwah et al., 2021; Phairuang, 2021; Valdés et al., 2013).

Spatial patterns of aerosols consistently showed highest concentrations in central commercial and industrial zones, with peripheral and southern areas recording lower levels. Unlike CO, aerosols tend to persist longer in the atmosphere, particularly under dry conditions and in areas with limited vegetation and poor waste management. Similar patterns have been documented in cities such as Delhi, Mumbai, Lahore, São Paulo, Quito, Accra, and Lagos (Vásquez et al., 2019; Fosu-Amankwah et al., 2021; Amaechi et al., 2024c).

## Synthesis and implications

Overall, both CO and aerosol concentrations were sensitive to changes in fuel consumption, mobility, and urban activity. Their similar seasonal and spatial patterns indicate shared combustion-related sources, though their atmospheric behaviour and persistence differ. These results demonstrate the utility of Sentinel-5P and Google Earth Engine for monitoring air quality in cities lacking ground-based infrastructure.

The identification of predictable seasonal peaks and spatial hotspots highlights the need for targeted interventions in Aba. Without deliberate air quality management, high concentrations in central commercial areas during the dry season could pose increasing environmental and public health risks. These findings provide a foundation for developing policy measures aimed at emission reduction, urban planning, and sustainable energy use.

## CONCLUSION

The present study successfully characterized the temporal and spatial dynamics of CO and aerosol concentrations in Aba from 2019 to 2024, providing continuous, pollutant-specific insights that previous ground-based or short-term studies could not achieve. The analysis revealed pronounced seasonal peaks, with February consistently exhibiting the highest concentrations for both pollutants, and clear inter-annual fluctuations linked to post-pandemic economic recovery and energy consumption patterns. Spatially, central commercial and industrial areas consistently emerged as pollution hotspots, while peripheral zones recorded lower levels, underscoring the influence of land use, population density, and local combustion sources on urban air quality.

A key novel contribution of this work lies in the integration of high-resolution satellite-derived Sentinel-5P data with GIS-based spatial analysis, enabling the identification of both

temporal trends and fine-scale spatial hotspots across the entire metropolis. This approach overcomes the limitations of previous localized, short-term measurements and generalized air quality indices, providing a robust, scalable methodology for continuous monitoring in developing cities with limited ground-based infrastructure.

The study fills a critical gap by delivering a multi-year, high-resolution assessment of urban air pollution in Aba, establishing a reference baseline for CO and aerosol dynamics that can inform evidence-based policy interventions. Both pollutants responded noticeably to anthropogenic activity and policy changes, such as fuel subsidy adjustments, and their accumulation and dispersion were clearly modulated by seasonal climatic factors.

These results reveal persistent gaps in understanding the fine-scale dynamics and drivers of urban air pollution in mid-sized cities. Continuous satellite monitoring combined with ground-based validation can support early-warning systems for air quality, while targeted interventions in identified hotspots can mitigate health and environmental risks. Furthermore, this methodology is transferable to other mid-sized cities in West Africa and the Global South, enabling comparative studies and regional-scale policy planning. Overall, the study establishes a foundation for integrated, data-driven urban air quality management that accounts for seasonal, spatial, and policy-driven variability.

## Author's statements

### Contributions

Conceptualization: C.F.A., F.O.E.; Data curation: C.F.A., F.O.E., A.K.O.; Formal and statistical analysis: all authors.; Investigation: all authors; Methodology: all authors; Resources: all authors, Writing original draft: C.F.A., F.O.E.; Writing – review and editing: all authors.

### Declaration of conflicting interest

The authors declare no competing financial or personal interests influencing the work reported in this paper.

### Financial interests

The authors declare they have no financial interests.

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### Data availability statement

The data used in this study are made available upon request from the corresponding author.

### AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

### Ethical approval declarations

Not applicable.

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