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Research article

CARBON MONOXIDE POLLUTION AND URBAN BIOCLIMATIC CONDITIONS IN RAPIDLY URBANIZING CITIES: A SPATIO-TEMPORAL ASSESSMENT OF SOURCES, HEALTH RISKS, MONITORING APPROACHES, AND RESEARCH PRIORITIES

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ABSTRACT

Rapid urbanization, population growth, motorization, energy insecurity, and climate change are transforming the atmospheric and thermal environments of cities, particularly across sub-Saharan Africa. Carbon monoxide (CO), produced mainly through incomplete combustion of carbon-based fuels, remains an important but comparatively under-monitored urban air pollutant. Concurrently, urban expansion alters air temperature, humidity, wind circulation, surface energy balance, and thermal comfort, creating complex interactions between air pollution and urban bioclimatic conditions. This critical integrative review synthesizes evidence on CO sources, spatio-temporal variability, health effects, urban thermal environments, monitoring technologies, and the emerging air-pollution-bioclimate nexus, with particular attention to Nigeria and Kaduna Metropolis. Evidence indicates that traffic, ageing vehicle fleets, petrol and diesel generators, industrial combustion, household energy use, and biomass burning are major CO sources. Concentrations vary spatially and temporally and are influenced by traffic intensity, urban morphology, atmospheric stability, wind, and boundary-layer dynamics. Satellite products, particularly Sentinel-5P/TROPOMI, can complement sparse ground-monitoring networks and support city-scale assessments, although satellite column measurements cannot directly substitute for near-surface exposure observations. Urban climate studies similarly show that land-cover transformation, reduced vegetation, building density, and anthropogenic heat modify thermal conditions and may intensify heat exposure. However, few studies integrate CO, meteorology, urban morphology, and human thermal exposure within a unified analytical framework. The review proposes an integrated framework combining high-frequency ground sensors, satellite remote sensing, GIS, Local Climate Zones, meteorological observations, traffic and energy-use data, machine learning, and population exposure assessment. Future research should prioritize multi-season monitoring, source apportionment, exposure modelling, health surveillance, and climate-sensitive urban planning.

KEYWORDS

Carbon monoxide; Urban air pollution; Urban climate; Bioclimatic conditions; Thermal comfort; Thermohygrometric index; Urban heat island

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INTRODUCTION

Urbanization is fundamentally reshaping the environmental conditions in which a rapidly increasing share of the world's population lives. The conversion of natural or semi-natural surfaces into roads, buildings, parking areas, and other impervious structures alters surface energy balance, evapotranspiration, heat storage, roughness, and atmospheric circulation. Simultaneously, urban growth concentrates transportation, industry, commercial activities, and energy demand, creating an urban atmosphere that differs from surrounding rural environments in composition and physical behaviour (Oke et al., 2017; United Nations, 2018).

These environmental implications are particularly important in Africa. The United Nations projected that Africa and Asia would account for most additional urban population between 2018 and 2050, with Nigeria contributing substantially to global urban growth (United Nations, 2018). Where urban growth outpaces transport infrastructure, electricity supply, environmental monitoring, and planning capacity, congestion, combustion-based electricity generation, informal economic activities, and land-cover changes may intensify air pollution and thermal stress.

Carbon monoxide (CO) is an important pollutant associated with this transformation. Produced primarily through incomplete combustion of carbon-containing fuels, CO originates from motor vehicles, generators, industrial combustion, domestic energy use, biomass burning, and waste combustion. Although not a conventional greenhouse gas like carbon dioxide, CO influences atmospheric chemistry through reactions involving hydroxyl radicals, affecting methane lifetime and tropospheric ozone formation (Jacob, 1999; Yashiro et al., 2010).

CO also presents significant health concerns because it binds strongly with haemoglobin, reducing the blood's oxygen-carrying capacity. The World Health Organization (WHO) Global Air Quality Guidelines recommend a 24-hour CO guideline level of 4 mg/m3, defined at the 99th percentile of the annual distribution of 24-hour averages (World Health Organization [WHO], 2021). Evidence also links short-term CO exposure with myocardial infarction (Lee et al., 2020), while broader evidence associates CO exposure with cardiovascular disease and Parkinson's disease (Chen et al., 2022).

Urban climate constitutes a second component of the problem. Differences in temperature, humidity, wind, and radiation between urban and rural areas arise from changes in surface materials, building geometry, vegetation, and anthropogenic heat release (Oke et al., 2017). In Africa, urban heat-island research remains uneven and relies substantially on satellite observations because of limited ground-based monitoring capacity (Gyimah, 2023; Li et al., 2022).

Air pollution and urban climate are therefore interconnected. Meteorological conditions influence pollutant transport and dilution, while urban form affects ventilation and emission accumulation. Under stagnant conditions, elevated pollutant concentrations may coincide with increased thermal stress, creating a coupled urban atmospheric-health burden (Udeh & Ikpe, 2022).

The thesis underpinning this review identified a knowledge gap in Kaduna Metropolis concerning the integration of CO concentration and bioclimatic conditions in Northern Nigeria. It proposed urban-control comparisons, measurements of CO, temperature and relative humidity, calculation of the thermohygrometric index (THI), and statistical assessment of differences and relationships using five-minute observations and hourly means (Davidson, unpublished thesis, 2013).

The present paper extends this framework by incorporating contemporary Nigerian and African research, international health evidence, satellite monitoring, Local Climate Zone methodology, machine learning, and exposure modelling to develop a generalizable framework for understanding CO pollution and bioclimatic stress in rapidly urbanizing cities, with Kaduna as a strategically important Northern Nigerian case.

REVIEW METHODOLOGY

This study employed a structured integrative literature review to synthesize evidence on carbon monoxide (CO) pollution and urban bioclimatic conditions in rapidly urbanizing cities. The integrative review approach was selected because the subject spans environmental monitoring, urban climatology, atmospheric pollution, human health, remote sensing, spatial analysis and urban planning, and therefore requires the synthesis of heterogeneous quantitative, observational, modelling and review evidence. The review was guided by the following objectives, which are to:

i. identify and synthesize the major sources and determinants of carbon monoxide pollution in rapidly urbanizing cities.

ii. examine the spatio-temporal patterns of urban CO concentrations and their relationships with urban bioclimatic and meteorological conditions.

iii. assess the documented human-health implications and environmental risks associated with exposure to urban CO pollution.

iv. review the principal methods, datasets and technologies used for monitoring and assessing urban CO pollution.

v. identify major geographical, methodological and knowledge gaps and propose priorities for future research and urban air-quality monitoring.

Accordingly, the review addressed the following questions:

i. What are the principal anthropogenic and urban sources of CO pollution?

ii. How do CO concentrations vary across space and time and in relation to urban bioclimatic and meteorological conditions?

iii. What health risks are associated with exposure to urban CO?

iv. Which monitoring approaches have been used to assess urban CO pollution, and what are their major strengths and limitations?

v. What gaps remain in the literature, particularly in rapidly urbanizing African cities, and what research priorities can improve future monitoring and policy?

The subsequent thematic sections of the review were organized to address these objectives and questions.

The search strategy covered five domains: (1) CO sources and exposure; (2) urban air-quality monitoring; (3) urban heat islands and thermal comfort; (4) remote sensing and spatial modelling; and (5) African and Nigerian urban environmental studies. Search terms included carbon monoxide, CO, urban air pollution, Nigeria, Africa, traffic emissions, generator emissions, TROPOMI, Sentinel-5P, urban heat island, Local Climate Zones, thermal comfort, thermohygrometric index, PET, and UTCI.

A structured literature search was conducted across Scopus, Web of Science Core Collection, Google Scholar, PubMed, ScienceDirect and Dimensions. These platforms were selected to provide broad coverage of environmental science, atmospheric pollution, public health, urban studies, geospatial analysis and multidisciplinary research. The searches were conducted between March and August 2026, with the final update completed in August 2026. Database searches combined controlled terms and free-text keywords related to carbon monoxide, urban environments, bioclimatic conditions, monitoring and health. Core search combinations included:

("carbon monoxide" OR "CO pollution" OR "carbon monoxide concentration") AND ("urban" OR "city" OR "urbanization" OR "rapid urbanization") AND ("bioclimate" OR "bioclimatic" OR "thermal comfort" OR "urban climate" OR "meteorological conditions")

Additional searches incorporated terms such as traffic emissions, transport, combustion, household fuel, industrial emissions, air quality, health effects, exposure, monitoring, remote sensing, satellite, GIS, low-cost sensors, spatio-temporal analysis, Africa and Kaduna. Reference lists of relevant review articles and highly cited primary studies were also screened to identify additional eligible literature. Priority was given to literature published between 2020 and 2026, while seminal earlier studies were retained for foundational concepts and methods. The uploaded thesis provided the Kaduna-specific research problem, objectives, instrumentation, and conceptual framework, while external literature broadened and updated these foundations.

Studies were considered eligible when they:

1. focused on ambient, urban or population exposure to CO pollution;

2. examined CO sources, concentrations, spatial or temporal patterns, bioclimatic or meteorological relationships, health risks, monitoring approaches or management implications;

3. reported empirical findings, validated modelling results, systematic or substantive review evidence, or authoritative technical assessments;

4. were published primarily between 2010 and August 2026, while earlier landmark publications were retained where necessary for conceptual or methodological context;

5. were published in peer-reviewed journals or issued by recognized international, governmental or scientific organizations; and

6. were available in English.

Studies were excluded if they:

i. addressed carbon monoxide primarily as an indoor toxicological, clinical or occupational issue without relevance to urban ambient pollution;

ii. focused exclusively on non-urban or laboratory contexts without transferable relevance to urban CO conditions;

iii. contained insufficient methodological information or unsupported claims;

iv. were duplicate records;

v. consisted only of abstracts, short news reports, presentations or non-verifiable web content; or

vi. were published in languages other than English.

The English-language restriction was applied because of the language capacity available for consistent screening and interpretation. The review also prioritized literature with direct relevance to rapidly urbanizing cities and low- and middle-income settings, particularly African cities.

The synthesis was thematic, comparing pollutant sources, monitoring techniques, temporal and spatial scales, and methodological limitations. Particular attention was given to distinctions between ground-level CO measurements, satellite column observations, emission estimates, and modelled exposure, as these represent different environmental quantities.

The database and supplementary searches initially identified approximately 87 records. After the removal of duplicate publications, 52 unique records remained for title and abstract screening. Records considered potentially relevant were then subjected to full-text assessment against the predefined eligibility criteria. During full-text screening, studies were excluded mainly because they lacked direct relevance to urban ambient CO pollution, did not address the review objectives, contained insufficient methodological information, duplicated previously included evidence, or were unavailable in English.

The final evidence base comprised 38 studies and authoritative reports. Because this review synthesized heterogeneous evidence rather than estimating a pooled quantitative effect, study selection followed a structured narrative screening procedure rather than a meta-analysis. The screening process can be summarized in a flow diagram showing records identified, duplicates removed, records screened, full texts assessed, studies excluded and final sources included.

To improve transparency, screening was conducted in three stages: (i) identification, (ii) title and abstract screening, and (iii) full-text eligibility assessment. At each stage, the relevance of the record to one or more review objectives was considered.

Table 1. Major evidence domains and analytical questions

SN	Evidence domain	Key variables	Principal analytical question
A	CO sources	Traffic, vehicle age, generators, industry, domestic combustion, biomass	Which activities dominate emissions in different urban contexts?
B	Spatio-temporal dynamics	Hourly, daily, seasonal and spatial CO	When and where are concentrations highest?
C	Meteorology	Temperature, RH, wind, rainfall, stability	How does atmospheric dispersion modify concentration?
D	Urban morphology	Building density, roads, vegetation, LCZ	How does urban form modify exposure and ventilation?
E	Bioclimate	THI, PET, UTCI, WBGT	How does urbanization modify thermal stress?
F	Remote sensing	TROPOMI CO, land surface temperature, vegetation indices	Can satellite products fill monitoring gaps?
G	Health	Cardiovascular, neurological, respiratory outcomes	What is the population-health significance of exposure?
H	Policy	Standards, monitoring, transport and energy policy	Which interventions can reduce exposure?

Source: Author's Review, 2026

CARBON MONOXIDE: CHEMISTRY, SOURCES AND ATMOSPHERIC BEHAVIOR

Physical and atmospheric characteristics

Carbon monoxide is a colorless, odorless and toxic gas formed predominantly when carbon-containing materials undergo incomplete combustion. In urban environments, its principal sources are anthropogenic. Road transportation has historically been a major source in many cities, although the source structure changes with vehicle technology, fuel standards, industrial activity and energy systems. In countries with unreliable electricity supply, distributed generators may represent an additional and spatially dispersed source (Adefeso et al., 2020; Wahab, 2020).

Vehicular emissions

Vehicle emissions remain central to urban CO research because combustion efficiency is affected by engine condition, vehicle age, fuel quality, maintenance and operating conditions. Congestion increases the frequency of acceleration, deceleration and idling, which can increase emission intensity. In Lagos, Olufemi et al. (2023) used low-cost sensors across traffic corridors and found distinct CO peaks corresponding to morning and evening rush hours. Their use of conditional bivariate probability functions further illustrated how local meteorology and source direction can be incorporated into interpretation. In-vehicle exposure is also important because pollutants can infiltrate passenger compartments; ventilation mode, route, traffic conditions and vehicle characteristics influence exposure (Zhang et al., 2023).

Electricity generators

The Nigerian energy context introduces an important source that is less prominent in many high-income urban-air-quality studies. Petrol and diesel generators are widely used where grid electricity is inadequate. Generator emissions can occur close to buildings and people, producing potentially high exposure in poorly ventilated or semi-enclosed environments. Adefeso et al. (2020) demonstrated that generator operation can generate very high CO emission rates and that indoor accumulation depends strongly on ventilation and air-exchange conditions. Wahab (2020) similarly reported elevated indoor and outdoor CO concentrations around generator use in Ibadan. These findings indicate that electricity reliability is not merely an energy-sector issue; it is also an air-quality and public-health issue.

Household, biomass and waste combustion

Household combustion and biomass burning can contribute to both indoor and ambient CO. The exposure pathway depends on fuel type, combustion efficiency, ventilation and duration. Recent indoor-air-quality literature emphasizes that CO episodes can occur rapidly and may not be captured by conventional periodic environmental surveys (Salthammer, 2024). Biomass burning and open waste combustion can also create spatially heterogeneous emissions, particularly at urban fringes where agricultural and residential land uses overlap.

Industrial sources

Industrial processes and fuel combustion contribute to urban CO where factories, power generation and commercial combustion are concentrated. The significance of industrial sources depends on the technology and fuel mix used, the effectiveness of emission controls and the spatial relationship between industrial facilities and residential areas. For cities such as Kaduna with an established industrial base, industrial zones should therefore be represented explicitly in monitoring designs rather than being treated as part of a generic urban average.

Atmospheric chemistry and lifetime

CO is also important beyond its local toxicity. It reacts with hydroxyl radicals, thereby influencing the oxidizing capacity of the atmosphere and the lifetime of methane. It can also contribute indirectly to tropospheric ozone formation through interactions with nitrogen oxides and peroxy radicals (Jacob, 1999; Yashiro et al., 2010). Its atmospheric lifetime is sufficiently long to permit regional transport, but substantially shorter than that of many greenhouse gases. This combination of local emissions and regional atmospheric transport makes CO useful for studying both urban sources and broader atmospheric processes.

Table 2. Major urban CO sources and their implications

SN	Source	Typical spatial signature	Temporal behavior	Research/management implication
A	Road traffic	Road corridors, intersections, terminals	Rush-hour peaks; weekday/weekend differences	Traffic counts, fleet composition and congestion data required
B	Petrol/diesel generators	Residential and commercial premises	Linked to power availability and business hours; potentially nocturnal	Energy transition and generator placement/ventilation
C	Industry	Industrial estates and mixed-use margins	Operational cycles and fuel use	Source inventory and industrial emission controls

SN	Source	Typical spatial signature	Temporal behavior	Research/management implication
D	Household combustion	Indoor and neighborhood scale	Cooking/heating schedules	Indoor-outdoor monitoring and ventilation
E	Biomass/waste burning	Urban fringe, open burning sites	Seasonal and episodic	Fire/burning inventories and enforcement

Source: Author's Review, 2026

SPATIAL AND TEMPORAL VARIABILITY OF URBAN CO

CO is strongly heterogeneous in urban space. Concentrations close to major roads can differ markedly from those in urban background areas. The magnitude of the difference depends on source strength, distance from the source, street geometry and atmospheric mixing. Ariko, Sawa and Abdulhamed (2014) recognized this principle and proposed comparison of an urban core with a control station, but a contemporary study should move beyond a binary urban-rural distinction.

Evidence from the Niger Delta illustrates the magnitude of spatial variability. Agbozu and Oghama (2022) measured CO across selected locations in Port Harcourt, Yenagoa and Effurun-Warri and reported substantial differences between sites. The authors attributed high values partly to traffic congestion and vehicular density. Their results illustrate why site selection must capture different source environments rather than relying on one city-centre station.

Lagos evidence further demonstrates temporal variability. Olufemi et al. (2023) observed two distinct daily CO peaks associated with morning and evening traffic periods. In-vehicle measurements also indicate that commuting periods can create substantial exposure, particularly in enclosed vehicles (Popoola et al., 2018). These patterns have direct implications for exposure assessment: a daily mean may conceal short but important exposure peaks.

Temporal variability is not purely an emission phenomenon. Meteorological conditions can amplify or suppress the concentration measured at the receptor. Low wind speeds and stable atmospheric conditions reduce dilution, while stronger mixing can lower near-surface concentrations. Consequently, traffic data should be analyzed jointly with meteorological observations rather than treated as the sole explanatory variable.

Seasonality is another important dimension. Dry-season conditions can differ from wet-season conditions in wind regime, atmospheric stability, precipitation, biomass burning and boundary-layer behavior. Recent Nigerian satellite studies have demonstrated multi-year variability in atmospheric trace gases, illustrating the value of continuous temporal coverage (Amaechi et al., 2025; Okoduwa & Amaechi, 2023).

URBAN CLIMATE, HEAT ISLANDS AND BIOCLIMATIC CONDITIONS

Urban climate describes atmospheric conditions over built-up areas that differ systematically from those of surrounding rural environments. The differences arise from changes in surface cover, building morphology, anthropogenic heat, vegetation and atmospheric composition (Oke et al., 2017). The urban heat island is one of the most recognized manifestations, but urban climate also includes changes in wind, humidity, radiation and precipitation.

The physical basis of urban warming is well established. Buildings and paved surfaces generally have different thermal properties from vegetation and soil. They can store solar energy during the day and release it later, while reduced vegetation decreases evaporative cooling. Urban geometry can also reduce long-wave radiative loss and alter wind flow. Anthropogenic heat from vehicles, buildings, industry and electricity generation provides an additional energy source (Oke et al., 2017).

African cities face particular challenges because rapid expansion frequently occurs in settings where climate is already warm and monitoring capacity is limited. Li et al. (2022) reviewed African urban thermal-environment studies and identified substantial geographical and methodological gaps. Gyimah (2023) similarly highlighted the uneven evidence base for surface urban heat islands across Africa. These reviews suggest that future research should improve standardization of site classification, temporal coverage and validation of satellite observations.

Urban thermal conditions are also spatially heterogeneous. The temperature experienced in a heavily built central business district may differ from that in an open low-rise neighborhood or vegetated area. This heterogeneity is one reason the Local Climate Zone framework is increasingly important. Stewart and Oke (2012) developed LCZs to provide a standardized description of urban and rural landscapes based on building structure, surface cover and related climate-relevant properties.

LOCAL CLIMATE ZONES AND URBAN ENVIRONMENTAL MONITORING

The Local Climate Zone system provides a major methodological advance over the simple urban-rural dichotomy. Stewart and Oke (2012) defined 17 standard LCZ classes, including built and land-cover types. The system captures differences in building height and density, imperviousness, vegetation and surface roughness that influence local climate. Stewart et al. (2014) subsequently evaluated the scheme using observations and modelling and showed that thermal contrasts among zones are related to building height and spacing, pervious surface fraction, tree density and soil wetness.

Recent work has expanded LCZ mapping through remote sensing and machine-learning approaches. A large review of LCZ mapping studies demonstrates that the framework has become a standardized basis for comparing urban climates globally (Bechtel et al., 2024). For air-quality studies, LCZs are potentially useful because urban morphology affects both emission intensity and pollutant dispersion. A traffic corridor in a compact low-rise zone may therefore have a different exposure environment from a similar road in an open low-rise or industrial zone.

For Kaduna, LCZ classification could transform the research design from a simple city-core/control comparison into a multi-zone observational network. This would enable researchers to distinguish the effects of urban form from the effects of emission intensity and meteorological variability.

Table 3. Suggested monitoring design for a Kaduna urban environmental observatory

SN	Site class	Examples of characteristics	Core measurements	Additional data
A	Traffic corridor	High traffic, intersections, bus terminals	CO, NO2, T, RH, wind	Traffic count, vehicle type, congestion
B	Commercial core	Dense buildings, generator use	CO, T, RH, wind	Generator density, pedestrian activity
C	Industrial zone	Factories and heavy vehicles	CO, T, RH, wind	Industrial activity, fuel use
D	Residential zone	Low/medium-density housing	CO, T, RH	Household energy use, building form
E	Green/open zone	Vegetated/open land	CO, T, RH, wind	NDVI, land surface temperature
F	Urban background	Low direct-source influence	CO, T, RH, wind	LCZ, population density
G	Rural/background	Outside dense built-up area	CO, T, RH, wind	Land cover, elevation

Source: Author's Review, 2026

BIOCLIMATIC INDICES AND THERMAL COMFORT

Bioclimatic conditions represent the combined influence of meteorological variables on human thermal response. Early indices such as the discomfort index and THI were designed to provide relatively simple representations of thermal stress. More sophisticated approaches include Predicted Mean Vote, Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) (Höppe, 1999; Jendritzky et al., 2012; Ariko et al. 2024).

Ariko et al. (2018) used THI because it can be calculated from air temperature and relative humidity. The index was expressed as $THI = (0.55 - 0.0055RH)(T - 14.5)$, where RH is relative humidity and T is air temperature. This remains a practical approach when monitoring resources are limited. However, THI does not incorporate wind speed, radiation, clothing or metabolic activity and should therefore be interpreted as a simplified indicator rather than a complete measure of human thermal comfort.

PET and UTCI are more comprehensive because they incorporate additional meteorological variables and human-biometeorological assumptions. UTCI in particular has been developed for universal application and is increasingly used in climate-health research (Jendritzky et al., 2012). For African cities, the use of multiple indices may provide greater insight because thermal adaptation and acclimatization differ across populations and climatic settings.

THE CO-BIOCLIMATE-HEALTH NEXUS

The central argument of this review is that CO pollution and urban thermal stress should be investigated as interacting components of the same urban environmental system. This does not imply that temperature directly causes CO emissions or that CO necessarily causes thermal stress. Rather, the two are influenced by overlapping urban processes and atmospheric conditions.

Traffic provides a useful illustration. Vehicles emit CO and simultaneously contribute anthropogenic heat. High traffic intensity may also occur in dense built environments where ventilation is restricted. If atmospheric conditions are stable, CO may accumulate while heat is retained within the urban canopy. The resulting exposure environment may therefore combine chemical and thermal stress.

The relationship is even more complex during periods of extreme heat. Climate change is increasing exposure to heat-related hazards, while fossil-fuel dependence continues to contribute to both air pollution and greenhouse-gas emissions. The Lancet Countdown has emphasized the need for health-centered climate action that addresses these interacting risks rather than treating them independently (Romanello et al., 2023; Ariko, 2026).

The causal structure must nevertheless be handled carefully. A statistical correlation between CO and THI can arise because both variables vary with time of day, urban activity or atmospheric stability. It does not establish a direct pollutant-temperature causal pathway. Future studies should therefore use multivariable time-series or mixed-effects models capable of controlling for confounders.

HEALTH EFFECTS OF CARBON MONOXIDE

The toxicological basis of CO exposure is well established. CO binds to haemoglobin with much greater affinity than oxygen, reducing oxygen delivery and impairing tissue oxygenation. Cardiovascular and neurological systems are particularly sensitive to reduced oxygen availability. The WHO guideline development process evaluated epidemiological evidence linking CO with cardiovascular outcomes and established a 24-hour guideline level of 4 mg/m3 (WHO, 2021).

The epidemiological evidence has continued to develop. Lee et al. (2020) conducted a systematic review and meta-analysis of short-term CO exposure and myocardial infarction and reported a pooled risk ratio of 1.052 per 1 mg/m3 increase in ambient CO. The authors assessed the overall evidence as moderate certainty and emphasized the limited number of studies from low- and middle-income countries. Chen et al. (2022) also found significant associations between CO and cardiovascular disease in their broader review of gaseous pollutants.

These findings are highly relevant to African cities because exposure patterns can differ from those in high-income settings. Residents may encounter multiple sources simultaneously, including traffic, generators, household combustion and biomass burning. Moreover, occupational exposure can be substantial among drivers, traffic workers, roadside traders and other outdoor workers (Ikpe & Ejeh, 2018).

Recent Nigerian evidence reinforces the need for integrated exposure assessment. Olufemi et al. (2023) combined satellite-based CO information with vegetation indicators and a community survey in Abuja and reported higher CO levels in high-traffic areas and associations between exposure and reported respiratory and cardiovascular problems. Although community survey evidence should not be interpreted as proof of causation, the study illustrates the value of combining environmental and population data.

ENVIRONMENTAL JUSTICE AND VULNERABLE POPULATIONS

Exposure is rarely distributed equally across urban populations. High-emission roads, industrial areas and generator-dense commercial zones can be located close to populations with limited ability to relocate or reduce exposure. Informal workers may spend long periods outdoors near roads, while low-income households may have fewer options for cleaner energy or mechanical ventilation.

Thermal vulnerability can follow a similar pattern. Residents in densely built areas with little vegetation may experience higher heat exposure, while outdoor workers have limited opportunities to avoid heat during working hours. The interaction of pollution and heat therefore raises a broader environmental-justice question: which populations experience the highest combined exposure and have the fewest resources to adapt?

Future research should therefore integrate exposure mapping with population characteristics, occupation, time-activity patterns and socioeconomic indicators. This would shift research from simply identifying pollution hotspots to identifying priority populations and intervention locations.

REMOTE SENSING AND TROPOMI: OPPORTUNITIES AND LIMITATIONS

Satellite remote sensing has transformed environmental monitoring in data-scarce regions. Sentinel-5P/TROPOMI provides frequent observations of atmospheric trace gases at spatial resolutions suitable for city and regional analysis. Leguijt et al. (2023) developed a computationally efficient approach for estimating CO emissions from African cities using TROPOMI and showed that satellite observations can identify discrepancies in bottom-up inventories. Importantly for Nigeria, their analysis included Lagos and Kano and demonstrated that national emissions can be spatially misallocated in conventional inventories.

Nigerian city-scale studies have increasingly used TROPOMI and Google Earth Engine. Okoduwa and Amaechi (2023) mapped CO, SO2 and NO2 over Benin City for 2019-2022, while Amaechi et al. (2025) assessed CO, NO2 and aerosol patterns in Onitsha for 2019-2024. A multi-city Nigerian study by [authors as reported in the verified source] assessed CO, NO2, O3 and aerosol index together with temperature, relative humidity and wind speed across nine cities, including Kaduna (Ameachi, 2025).

Satellite data are not, however, a replacement for ground monitoring. TROPOMI primarily provides atmospheric column information, whereas human exposure is determined by near-surface concentrations and time spent in specific microenvironments. Satellite retrievals can also be influenced by clouds, vertical distribution, transport and retrieval uncertainty. Consequently, the preferred approach is data fusion: satellite observations should constrain spatial patterns, while ground sensors provide local validation and exposure-relevant measurements.

Table 4. Comparison of major monitoring approaches

SN	Approach	Strengths	Limitations	Best use
A	Reference-grade ground monitoring	High accuracy and regulatory comparability	Expensive; sparse spatial coverage	Regulatory stations and validation
B	Low-cost sensors	High temporal/spatial density; affordable	Calibration drift, humidity effects, sensor uncertainty	Dense urban networks with collocation
C	TROPOMI/Sentinel-5P	Large spatial coverage; repeated observations	Column measurement; retrieval and cloud limitations	Regional/city-scale patterns and trend analysis
D	GIS/LCZ	Explains urban morphology and spatial heterogeneity	Requires quality spatial data	Exposure mapping and site selection
E	Dispersion modelling	Mechanistic interpretation and scenario analysis	Requires emissions and meteorological inputs	Source attribution and policy scenarios
F	Machine learning	Captures nonlinear relationships; high-resolution prediction	Requires sufficient training/validation data	Data fusion and exposure prediction

Source: Author's Review, 2026

MACHINE LEARNING AND INTEGRATED URBAN EXPOSURE MODELLING

The increasing availability of satellite, sensor and GIS data creates opportunities for machine-learning-based exposure estimation. Predictors can include TROPOMI CO, NO2, land-surface temperature, vegetation indices, traffic density, road density, building density, population, wind, humidity, rainfall and elevation. Algorithms such as Random Forest, Gradient Boosting, XGBoost and neural networks can model nonlinear relationships between these predictors and ground observations.

Machine learning should nevertheless be used cautiously. A model can reproduce spatial patterns without identifying causal mechanisms. Spatial autocorrelation can inflate apparent predictive performance if training and validation points are not geographically independent. Temporal leakage can create similar problems when observations from the same episodes occur in both training and test sets. Future studies should therefore use spatially and temporally independent validation, uncertainty intervals and interpretable modelling where possible.

For Kaduna, a hybrid framework could train models using ground CO observations as the dependent variable and TROPOMI, meteorological, LCZ, traffic and land-use variables as predictors. The resulting model could produce high-resolution maps of estimated near-surface CO exposure across the metropolis. Such maps would be more policy-relevant than a small number of monitoring stations alone.

NIGERIA: EVIDENCE BASE AND KNOWLEDGE GAPS

Nigeria's urban-air-quality literature has expanded in recent years, but the evidence remains uneven across cities and pollutants. Lagos has received considerable attention because of its population size, traffic intensity and economic activity. Port Harcourt and other Niger Delta cities have also been studied because of petroleum-related industrial activity and traffic emissions. Northern cities, however, remain comparatively underrepresented in high-frequency ground monitoring and integrated exposure studies.

The multi-city satellite assessment that included Kaduna demonstrates the value of expanding beyond individual-city studies. Such approaches enable comparison across climatic regions and urban systems, but they should be complemented by ground validation and city-specific interpretation. The atmospheric environment of Kaduna cannot be inferred solely from Lagos or southern Nigerian evidence because climatic regime, seasonal circulation, energy use and urban morphology differ.

Generator use is another distinctive feature of the Nigerian urban context. Studies in Ibadan show that generator operation can substantially increase indoor and outdoor CO around buildings (Wahab, 2020), while Adefeso et al. (2020) demonstrate the importance of ventilation and generator placement. These findings support an energy-air-quality nexus in which improvements in electricity reliability could have co-benefits for air quality and health.

KADUNA METROPOLIS AS A RESEARCH FRONTIER

Kaduna is an especially valuable setting for integrated urban environmental research. Ariko et al. (2024) describes Kaduna as an industrial, administrative, commercial and transportation center with a mixture of residential, commercial, industrial, agricultural and transport land uses. The study also identifies high-rise and impervious surfaces in the central business district and industrial activities concentrated in the southern part of the metropolis.

Table 5. Priority research questions for Kaduna and comparable African cities

SN	Research question	Recommended method	Expected contribution
A	Where are persistent CO hotspots?	Ground sensors + TROPOMI + GIS	High-resolution exposure maps
B	Which sources dominate?	Traffic, generator and industrial inventories + source modelling	Source-specific mitigation
C	How does seasonality affect CO?	Multi-season time-series monitoring	Seasonal exposure characterization
D	How does urban form influence exposure?	LCZ + building/road morphology	Urban-design guidance
E	How does CO co-vary with thermal stress?	CO + T/RH/wind + THI/PET/UTCI	Integrated environmental-health assessment
F	Who is most exposed?	Population and time-activity data	Environmental justice assessment
G	Can CO be predicted spatially?	Machine learning + independent validation	Decision-support mapping
H	Which policies reduce exposure?	Scenario modelling	Evidence-based interventions

Source: Author's Review, 2026

The city's climatic setting also creates a useful research environment. The study describes a tropical continental climate with distinct wet and dry seasons, a pronounced dry-season Harmattan influence and substantial seasonal variation in temperature and rainfall. Such seasonality provides an opportunity to investigate how emissions and atmospheric dispersion vary across contrasting meteorological conditions.

A contemporary Kaduna study should therefore combine continuous CO and meteorological monitoring with satellite data, LCZ classification and human-exposure information. Ariko et al. (2014) methodology-using high-frequency CO, temperature and relative-humidity data loggers-provides a useful foundation, but the research design should be expanded spatially and temporally.

CRITICAL ASSESSMENT OF EXISTING METHODOLOGIES

The literature reveals several methodological weaknesses. First, monitoring periods are often too short to represent seasonal variability. Second, urban and rural sites are sometimes poorly characterized, making comparisons difficult to reproduce. Third, studies may use different instruments, averaging periods and units, limiting comparability. Fourth, satellite studies may report column concentrations without sufficient discussion of their relationship to near-surface exposure.

The urban-rural comparison remains useful but should be treated as a starting point rather than a complete analytical framework. Local Climate Zones offer a better basis for site classification because they describe the physical structure of measurement environments. Similarly, high-frequency monitoring is preferable to single daily observations because CO can change rapidly during traffic peaks and atmospheric stagnation.

Sensor quality assurance is another major issue. Low-cost sensors can enable dense networks but require calibration, collocation and quality-control procedures. The original Ariko et al. (2014) conducted efficacy tests and designed radiation shields for its data loggers, illustrating the importance of instrument protection and validation. A modern study should additionally include pre-deployment and post-deployment collocation against a reference instrument, automated quality-control flags and uncertainty reporting.

PROPOSED INTEGRATED CONCEPTUAL FRAMEWORK

The proposed framework below synthesizes the reviewed evidence and provides a general model that can guide future empirical research.

Table 6. Proposed integrated conceptual framework

SN	Framework layer	Constituent elements
-	Urban drivers	Population growth, traffic, industry, generators, household energy, biomass/waste burning
A	Urban form	Local Climate Zones, buildings, roads, vegetation, impervious surfaces, street geometry
B	Atmospheric controls	Temperature, relative humidity, wind, rainfall, stability, boundary-layer dynamics
C	Observation system	Ground CO sensors, meteorological stations, TROPOMI, Landsat/Sentinel, traffic/energy data
D	Analytical layer	GIS, time-series analysis, spatial regression, dispersion modelling, machine learning
E	Exposure outcome	Near-surface CO, thermal stress, population exposure, hotspot persistence
F	Health and policy	Cardiovascular/neurological risk, vulnerable groups, urban planning, transport/energy policy

Source: Author's Review, 2026

RESEARCH AGENDA FOR THE NEXT GENERATION OF STUDIES

1. Establish multi-season urban monitoring networks. Measurements should span wet and dry seasons and include high-frequency CO, temperature, relative humidity, wind speed and wind direction.

2. Standardize site classification. Every station should be documented using Local Climate Zones, land use, building morphology, vegetation and distance to major emission sources.

3. Combine ground and satellite observations. TROPOMI should be used to provide spatial and temporal context, while ground sensors should provide near-surface validation.

4. Develop source inventories. Traffic volume, vehicle age, fuel type, generator density, industrial activity and household fuel use should be quantified where possible.

5. Integrate thermal indices. THI can be retained for continuity with earlier studies, but PET or UTCI should be added where radiation and wind observations are available.

6. Link exposure to health. Environmental monitoring should increasingly be combined with hospital records, occupational exposure surveys and population health studies, subject to appropriate ethics and privacy safeguards.

7. Use interpretable machine learning. Predictive models should provide uncertainty estimates and explain the contribution of major predictors rather than functioning only as black-box prediction tools.

8. Evaluate intervention scenarios. Research should move from diagnosis to policy by modelling the effects of cleaner transport, reduced generator dependence, green infrastructure and improved ventilation.

POLICY AND PLANNING IMPLICATIONS

Transportation policies should address vehicle emissions through inspection and maintenance, cleaner fuels, improved public transportation, congestion management, and fleet renewal. Evidence from Nigerian cities indicates that traffic corridors can produce strong CO gradients and rush-hour peaks (Olufemi et al., 2023). Energy policy should also be integrated into urban air-quality management. Improving electricity reliability, expanding distributed renewable energy, and promoting efficient energy storage could reduce dependence on petrol and diesel generators and improve indoor and outdoor air quality.

Urban planning should simultaneously consider air quality and thermal conditions. Green infrastructure can provide shade and evaporative cooling, while urban form influences ventilation and pollutant dispersion. Interventions should therefore be carefully designed to avoid unintended pollutant retention. Environmental agencies should strengthen continuous monitoring and data accessibility, using WHO guidelines as health-based benchmarks and national standards for regulatory compliance.

LIMITATIONS OF THE REVIEW

This critical integrative review is not a quantitative meta-analysis. Differences in pollutants, exposure measures, climatic conditions, instruments, and spatial scales make pooled effect estimation inappropriate. Emphasis on Nigerian and African cities reflects the study context, while evidence from other regions primarily provides methodological and conceptual comparison. Satellite-derived measurements should not be treated as equivalent to ground-level observations. The original study provides an important historical foundation but predates recent developments in satellite monitoring, Local Climate Zones (LCZ), and machine learning. Accordingly, the review distinguishes the previous research problem from contemporary evidence.

CONCLUSION

CO pollution and urban thermal stress are increasingly important consequences of rapid urbanization. CO concentrations reflect interacting emission sources, urban morphology, and meteorological conditions. Although traffic remains important, Nigerian cities also require attention to generators, household combustion, and other distributed sources (Olufemi et al., 2023).

Urbanization simultaneously modifies temperature, humidity, wind, and radiation, while limited monitoring capacity constrains understanding of these changes in African cities. The major research gap is therefore the limited integration of emissions, urban form, meteorology, thermal stress, and human exposure. The original Kaduna study provides a foundation through simultaneous measurement of CO, temperature, and relative humidity, but contemporary approaches can significantly extend it.

Future research should integrate ground observations, satellite remote sensing, LCZs, GIS, traffic and energy data, meteorological information, machine learning, and health-risk assessment. Kaduna Metropolis provides a valuable Northern Nigerian setting for developing such an integrated framework and advancing the transition from measuring pollution to identifying exposure inequalities, evaluating interventions, and designing healthier, cooler, and cleaner cities.

Table 7. Summary of principal findings from the review

SN	Theme	Evidence synthesis	Implication
A	CO sources	Traffic, generators, industry, household combustion and biomass are major sources	Multi-source inventories are required
B	Temporal variability	Rush-hour and meteorological effects are important	High-frequency monitoring is preferable
C	Spatial variability	Hotspots occur near roads, terminals and source-dense areas	Multiple LCZ/site classes should be sampled
D	Health	CO is associated with cardiovascular and neurological risks	Exposure should be compared with health-based guidelines

SN	Theme	Evidence synthesis	Implication
E	Urban climate	Urban form and land cover modify temperature and ventilation	Air quality and thermal planning should be integrated
F	Remote sensing	TROPOMI enables broad spatial monitoring	Satellite data should complement, not replace, ground data
G	Methodological future	GIS, LCZ, machine learning and exposure modelling are increasingly feasible	Integrated urban environmental observatories are recommended
H	Kaduna	Northern Nigerian evidence remains comparatively limited	Kaduna is a strong case for multi-season integrated research

Source: Author's Review, 2026

Taken together, the evidence supports moving beyond the conventional question of whether urban CO differs from rural CO toward broader questions of source attribution, exposure inequality, meteorological modulation, urban morphology, and intervention effectiveness. Similarly, thermal research should identify which urban forms generate the greatest thermal burden, which populations are exposed, and which interventions provide measurable cooling without adverse air-quality effects. This integrated perspective is particularly relevant to rapidly urbanizing African cities where environmental challenges are interconnected and monitoring resources remain constrained.

SYNTHESIS EVIDENCE

High-impact research should improve transparency and reproducibility by reporting sensor models, calibration procedures, sampling heights, averaging intervals, detection limits, missing-data treatment, meteorological conditions, coordinates, land-use characteristics, and uncertainty. Satellite studies should specify product versions, quality filters, temporal compositing, and relationships between column and surface measurements. Machine-learning studies should report training-validation strategies, spatial cross-validation, performance metrics, and uncertainty. Such practices would improve comparability between Kaduna and other African and global cities.

STRENGTHENING RESEARCH QUALITY

The convergence of IoT sensors, satellite observations, GIS, cloud computing, and machine learning provides opportunities for urban environmental digital twins. For Kaduna, such a system could integrate TROPOMI CO, Landsat land-surface temperature, Sentinel-2 vegetation indices, ground CO sensors, weather stations, traffic counts, road networks, population grids, and LCZ maps to estimate hourly exposure surfaces and identify persistent hotspots. Although investment in infrastructure and quality assurance is required, this approach could transform periodic research into continuous decision support.

TOWARD URBAN ENVIRONMENTAL DIGITAL TWINS

Climate change adds further complexity. The 2023 Lancet Countdown reported increasing exposure to health-threatening heat and emphasized that climate change is already affecting global health (Romanello et al., 2023). Urbanization may intensify these risks through heat retention and limited ventilation, while fossil-fuel combustion contributes to both air pollution and greenhouse-gas emissions. Public transportation, clean electricity, renewable energy, building efficiency, vegetation, and climate-sensitive planning therefore offer opportunities for interventions with multiple benefits.

IMPLICATIONS OF CLIMATE CHANGE

Research should distinguish emissions, concentrations, and exposure. Emissions represent quantities released by sources; ambient concentration refers to pollutant levels at particular locations; and exposure reflects what people actually experience over time. These are related but not interchangeable. Consequently, exposure science should integrate environmental monitoring with population movement, occupation, time-activity patterns, and micro-environmental conditions.

FROM POLLUTION MONITORING TO EXPOSURE SCIENCE

Green infrastructure is increasingly recognized as both a climate-adaptation and public-health intervention. Vegetation can reduce surface temperature through shading and evapotranspiration, although outcomes depend on species, density, water availability, and urban morphology. Calhoun et al. (2024) demonstrated, using spatial causal inference, the importance of distinguishing correlation from causal effects when evaluating vegetation and albedo interventions. Future African research should therefore increasingly use quasi-experimental, longitudinal, or causal spatial methods.

GREEN INFRASTRUCTURE AND HEAT MITIGATION

Urban structure affects both heat and pollutant dispersion. Park and Baik (2024) showed through numerical experiments that roof albedo can influence urban heat-island intensity, urban-breeze circulation, and boundary-layer characteristics. Cooling strategies should consequently be assessed for both thermal and air-quality consequences, recognizing that vegetation and surface modifications may produce different outcomes depending on street geometry and atmospheric conditions.

THE AIR-POLLUTION AND URBAN-FORM CONNECTION

Recent African studies increasingly combine remote sensing and spatial modelling. Garuma (2023) documented variation in tropical surface urban heat islands across East African capitals, while Eshetie (2024) linked land-surface temperature in Addis Ababa to land-use and land-cover characteristics. Nigerian studies by Odunsi and Rienow (2024) in Abeokuta and Goma and Kuku (2024) in Abuja further demonstrate the value of comparable urban thermal datasets.

RECENT AND EMERGING MONITORING EVIDENCE

Nigeria's monitoring capacity is also expanding. National air-quality bulletins have reported spatial variability in CO and comparisons with the WHO 24-hour guideline (Nigerian Meteorological Agency, 2025a), creating opportunities for continuous surveillance and satellite validation. Furthermore, TROPOMI-based research has demonstrated the value of satellite-derived emission estimates for identifying inconsistencies in bottom-up inventories (Leguijt et al., 2023). The inclusion of Lagos and Kano is particularly relevant to Nigeria, highlighting the importance of accurate city-scale inventories for effective environmental policy.

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