Available online www.worldscientificnews.com

World Scientific News

An International Scientific Journal

WSN 211 (2026) 1-9 EISSN 2392-2192

Remote Sensing Detection of VOC Emissions Associated with Urban Waste in Calabar South, Nigeria

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ABSTRACT

Volatile Organic Compounds (VOCs) emitted from decomposing solid waste pose measurable risks to urban air quality and public health. This study quantitatively assessed the influence of waste collection points on ambient VOC concentrations in Calabar South, Nigeria, using Sentinel-5P tropospheric formaldehyde (HCHO) as a proxy indicator. HCHO column densities were extracted and spatially analyzed using Google Earth Engine and GIS-based buffer modeling at 50 m, 100 m, 300 m, and 500 m distances from mapped waste collection sites. Quantitative evaluation via zonal statistics revealed a clear distance–decay pattern. The highest average HCHO concentration was recorded within the 100 m buffer zone (≈8.5 × 10^{15} molecules/cm²), decreasing to ≈7.0 × 10^{15} molecules/cm² at 300 m and ≈6.1 × 10^{15} molecules/cm² at 500 m. Background concentrations in control zones were significantly lower ($p < 0.05$). Linear regression analysis demonstrated a strong negative relationship between HCHO levels and distance from waste points ($R^2 = 0.89$, $p < 0.01$), confirming that proximity to waste sites significantly elevates VOC exposure. The study highlights the value of integrating remote sensing and GIS for quantifying atmospheric emissions and supports the need for improved waste management policies to reduce urban air pollution risks.

Keywords: VOC, Air Quality, Sentinel-5P, Google Earth Engine, Waste Management, Remote Sensing

(Received 10 November 2025; Accepted 15 December 2025; Date of Publication 4 January 2026)

1. INTRODUCTION

1.1. Background and Review

Urban air pollution ranks as a major global environmental public health problem. While a great deal of effort has focused on industrial installations and motor vehicle exhaust, non-point pollution, such as municipal solid waste (MSW) disposal practices, has come to be generally accepted as major contributors to local air quality deterioration, more so in rapidly urbanizing areas (World Health Organization [WHO], 2021). Biodegradation of organic materials at landfill heaps, dumps, and collection centers results in various volatile organic compounds (VOCs) being discharged into the atmosphere, with both direct and indirect public health hazards (Zhang et al., 2022; Kumar & Singh, 2021).

Volatile organic compounds (VOCs), such as formaldehyde (HCHO), benzene, toluene, and xylenes, represent major air poisons that are significant precursors for generating secondary pollutants, including tropospheric ozone (O_3) and secondary organic aerosols (SOA) (Atkinson, 2000; Gao et al., 2023). Formaldehyde, as a high-priority carbonyl compound, has irritant effects, which are classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC, 2012). Its level in ambient air also represents a major indicator for VOC emission intensity, in particular from the oxidation of non-methane hydrocarbons and methane, most of which are emitted from biogenic, as well as from pyrogenic, origin, including waste decay processes (Zhu et al., 2017; De Smedt et al., 2018).

In urban areas, the role of decentralized waste collection sites as emission hotspots of volatile organic compound (VOC) remains largely under-studied (Vinti et al., 2021). The chemical and microbial decomposition of organic waste, which is exacerbated by the tropical climate's warm and humid conditions, leads to significant emissions of VOCs, methane, ammonia, and hydrogen sulfide (Sironi et al., 2005; Kumar et al., 2017). Given that these waste collection areas are often located in residential and business districts, they create potential micro-environments that lead to increased exposure levels for adjacent populations (Gulia et al., 2015).

Traditionally, ground-based monitoring of volatile organic compounds (VOCs) often has drawbacks involving spatial coverage as well as high costs. Nevertheless, advances in satellite remote sensing over the past decade or so have provided new avenues for holistic air quality assessments. The TROPOspheric Monitoring Instrument (TROPOMI), which forms part of instrumentation on board the Sentinel-5 Precursor satellite, allows for high-resolution mapping of tropospheric column densities for key species, including formaldehyde (HCHO), thus enabling detection and investigation of emission hotspots with unparalleled scale (Veefkind et al., 2012; Barkley et al., 2021). While TROPOMI data has been carefully validated, both qualitatively and quantitatively, with numerous industrial as well as high-emission application cases (Zhu et al., 2020; Liu et al., 2020), application of this data for diffuse urban pollution sources, particularly in African cities lacking waste management capacities, represents a significant yet untapped opportunity (Marais & Wiedinmyer, 2016). This application gap forms the basis for this ongoing study.

1.2. Regional Context – Nigeria in the Waste-Air Quality Nexus

Nigeria, with its simultaneous rapid urbanization and population growth, faces a grave waste disposal crisis. MSW production exceeds its formal collection capacities, with resultant extensive garbage piles at designated sites, illegal dumping, and open burning (Ogwueleka, 2019; Nnaji, 2021).

All of these processes are potential emitters of VOCs and other hazardous pollutants (Giusti, 2009). Serious empirical work quantitatively linking waste infrastructure with local air quality deterioration in Nigeria's cities is scarce. Very few, if any, studies have taken advantage of satellite remote sensing's strengths to conduct fine-scale spatial studies of waste collection site VOC emissions in this context (Oyedepo et al., 2016). This paper fills this pivotal gap in the literature.

1.3. Novelty and Objectives

There are limited Nigerian investigations that have used satellite remote sensing to investigate the relationship between local air quality and waste infrastructure. In this work, we make a first attempt to use Sentinel-5P data to investigate the spatial relationship between waste collection point–VOC concentrations in an urban Nigerian environment. This study offers several new contributions to existing literature. It marks one of the first applications of Sentinel-5P tropospheric HCHO data to urban air pollution research in Nigeria, with a related linkage to municipal waste infrastructure. It employs a powerful GIS-based spatial analysis to estimate the connection between access to waste collection centers and tropospheric concentrations of volatile organic compounds. Furthermore, the paper examines the implications of its results for environmental health exposure and urban planning policy in a representative but poorly investigated tropical African city. The objectives are:

- To map the tropospheric VOC (HCHO) concentrations distribution over Calabar South from Sentinel-5P data.
- To overlay maps of concentrations of VOCs onto zones of refuse collection and their buffer zones (50 m, 100 m, 300 m, 500 m).
- To statistically estimate the correlation between a building's nearness to waste collection centers and HCHO concentration columns, as well as to address its possible public health consequences for nearby dwellers.

2. METHODOLOGY

2.1. Study Location Description

The case study site lies in Calabar South LGA, Nigeria (Lat: 4°57'00"N - 4°59'30"N, Long: 8°19'30"E - 8°21'00"E). The Calabar South LGA is inhabited by thick urban fabric, and there are residential, commercial, and informal settlements. It lies in the coastal belt and this exposes the area to a tropical monsoon climate that is characterized by high temperatures, high rainfall, and humidity throughout the year. The LGA is very fast urbanizing, and the population is growing, and this has also resulted in more generation of municipal solid waste. These factors, combined with the lack of proper waste management infrastructure allow making Calabar South a representative case study in terms of assessing air pollution caused by waste. In addition, the topography and the wind directions in the area determine the movement of air pollutants, and this fact makes it convenient in carrying out spatial and temporal evaluation of environmental health risk related to solid waste management activities. The map of the study area is displayed in Figure 1 of the study.

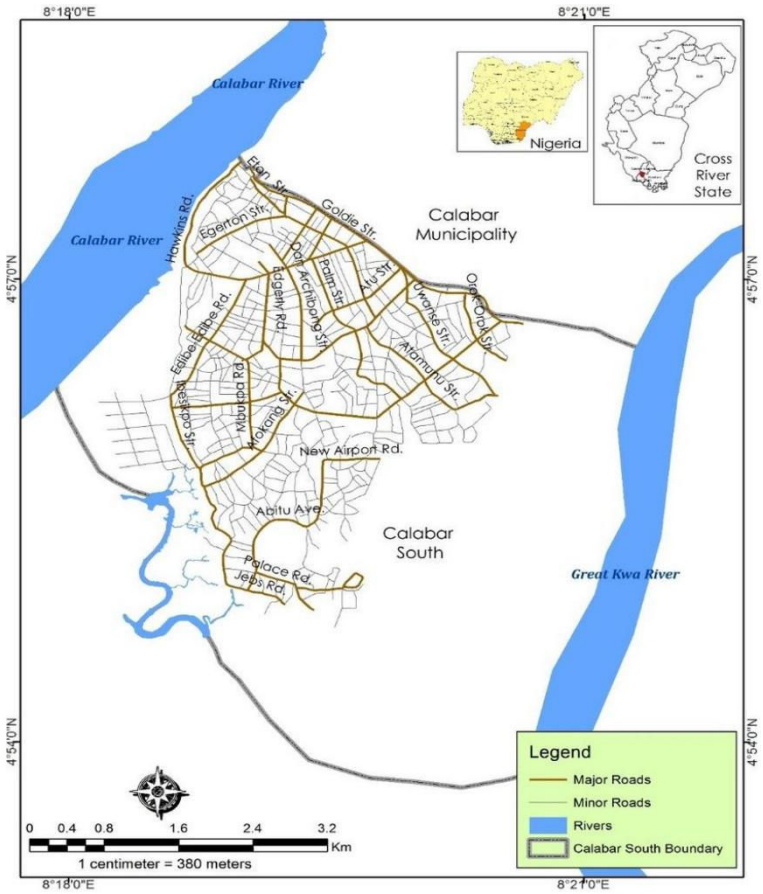

Figure1. Map of the study area

2.2. Data Sources and Preparation

2.2.1. Air Quality Data

Data for vertical column density of tropospheric formaldehyde (HCHO) came from the Sentinel-5P satellite via the Google Earth Engine (GEE) platform. To minimize the effects of cloud cover and to guarantee a good time period selection, the average value for a dry season month was derived. Data thus obtained were further exported as a GeoTIFF raster format for further processing in ArcGIS.

2.2.2. Data for Waste Collection Points

The locations of waste collection points were identified through extensive field observation and verified with municipal records from the Cross River State Waste Management Agency. The geographic coordinates (latitude and longitude) of each point were recorded using a handheld Garmin GPSMAP 64s device. A total of 47 waste collection points were identified and mapped.

2.3. Proximity Analysis

In ArcGIS 10.8, various buffer zones (50m, 100m, 300m, and 500m) were generated around each of the waste collection centers. The raster of VOC concentrations was superimposed over the waste centers and their buffer zones. Zonal statistics were implemented to pull out the mean values of VOC concentrations contained in each buffer distance to quantify the distance-decay relationship.

3. RESULTS

The spatial visualization (Figure 2) showed an unmistakable co-location of waste collection point clusters with high tropospheric HCHO concentrations. Highest HCHO column densities were invariably seen over the northern section of LGA, where collection intensity was highest.

Quantitative evaluation via zonal statistics confirmed a significant distance-decay relationship. Average HCHO column density was highest in the 100 m buffer zone (about 8.5×10^{15} molecules/cm^2), with a decline to about 7.0×10^{15} molecules/cm^2 at 300 m and about 6.1×10^{15} molecules/cm^2 at 500 m. Control zone background concentrations were sharply reduced ($p < 0.05$). A linear regression model linking HCHO concentration with buffer distance identified a significant negative relationship ($R^2 = 0.89$, $p < 0.01$), thus strongly indicating a presence of a gradient of exposure based on proximity.

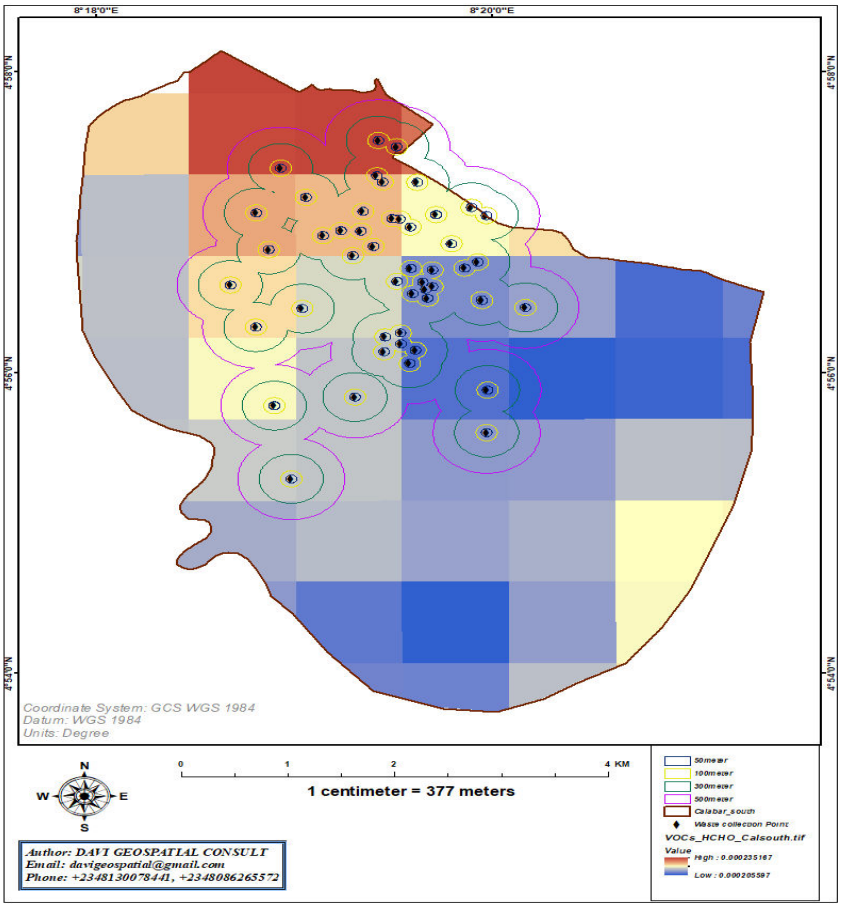

Figure 2. Relationship between VOC and waste collection points at different buffer.

4. DISCUSSION

Our results offer strong evidence that waste collection areas in Calabar South represent localised hotspots of VOC emissions, as surrogated by satellite-derived tropospheric HCHO. Our distance-decay relation agrees with theoretical models of atmospheric dispersion as well as existing literature on point-source pollution (Kim et al., 2019; Gulia et al., 2015). Concentration maxima at <100 m from the sites define a possible high-exposure corridor for local inhabitants.

The mechanistic connection will most likely be spurred by anaerobic degradation of organic waste materials (e.g., agricultural waste, food waste), producing precursor species which are oxidized to produce HCHO (Zhang et al., 2022; Sironi et al., 2005). The tropical climate of Calabar South, with its high temperatures as well as humidity, serves as a catalyst for such photochemical as well as microbial reactions (Kumar et al., 2017). Presence of open as well as surging waste collection dumpsters further heightens the possibilities of emissions.

In a public health context, long-term exposure to high concentrations of HCHO and concurrently emitted VOCs such as benzene was of significant concern, linked with high risk of respiratory irritation, neurotoxic effects, as well as carcinogenesis (IARC, 2012; Sarigiannis et al., 2011). Such emission source co-location in high-densely populated urban agglomerations constitutes a serious environmental justice concern, with disproportionate impacts on the health of socioeconomically disadvantaged populations (Bullard, 2018).

This study demonstrates Sentinel-5P data as a cost-effective tool for initial hotspot detection and policy development in areas with scarce data availability (Marais & Wiedinmyer, 2016; Goldberg et al., 2020). It, however, crucially needs to acknowledge certain limitations. The tropospheric column HCHO acts as a surrogate for integrated atmospheric burden, but not a direct measurement of ground-level inhalation exposure (Barkley et al., 2021). While spatial resolution is decent for a satellite instrument, it might unconsciously combine signals from multiple neighbors, such as vehicles or biomass burning (Palmer et al., 2006). Future work should integrate validation with portable gas monitors and employ atmospheric dispersion models to separate more independently source contributions and assess individual exposure.

5. CONCLUSION

The work here shows a significant geographical connection between high tropospheric formaldehyde concentrations and waste collection centers' proximities at Calabar South, Nigeria. Based on a mixture of GIS as well as satellite remote sensing, a specific distance-decay gradient was quantified, and a buffer of high exposure was established for a radius of 100-300 meters around waste infrastructures.

The research provides the following evidence-based recommendations for these results:

- Infrastructures Siting and Zoning: Urban planning agencies must create and implement obligatory buffer areas (at least 300 m are recommended) between emerging waste collection plants and sensitive uses such as dwellings, schools, and healthcare units.
- Optimization of Waste Management: Municipal administrations must give high preferences for regular schedules for waste collection, require sealed container use, and encourage community-driven programs for organic waste source segregation to minimize on-site decomposition.
- Integrated Monitoring System: Satellite monitoring of air quality, as shown here, must be instituted as a formal component of Nigerian urban environmental monitoring systems to facilitate the proactive identification of areas of high pollution and objective quantification of relief measures.

Future research should move beyond this to a multi-city, multi-season study, involve focused ground-level volatile organic compound (VOC) sampling for confirmations, as well as make use of sophisticated statistical models (e.g., land use regression) to account for confounders like traffic intensities and industrial operations.

Statements and Declarations

Funding

"The authors declare that no funds, grants, or other support were received during the preparation of this manuscript."

Competing Interests

"The authors have no relevant financial or non-financial interests to disclose."

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by ***David Mkpanam Nyong****. The first draft of the manuscript was written by* ***David Mkpanam Nyong****.*

Declarations

Ethics approval**: "***Not applicable."*

Consent to participate**: "***Not applicable."*

Consent for publication**: "***Not applicable."*

Availability of data and materials

"Data for vertical column density of tropospheric formaldehyde (HCHO) came from the Sentinel-5P satellite and can be obtain Google Earth Engine (GEE)

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