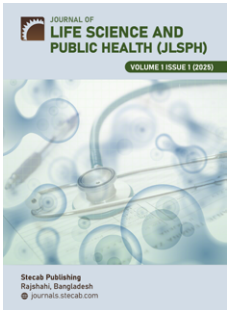

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Volatile Organic Compounds from Gas Flaring and Their Atmospheric Implications in the Niger Delta

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About Article

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ABSTRACT

This study investigates volatile organic compounds (VOCs) emitted from gas flaring in the Niger Delta, focusing on their atmospheric lifetimes and transformation pathways under tropical conditions. Field measurements combined with photochemical modelling (MCM v3.3.1 coupled with AERMOD) revealed accelerated degradation of BTEX compounds, with lifetimes shortened to 2–12 hours compared with 6–18 hours in temperate regions. Elevated solar radiation and hydroxyl radical concentrations were identified as the main drivers of rapid secondary pollutant formation. Secondary organic aerosols (SOAs) reached nearly double the World Health Organization (WHO) guideline, while ground-level ozone exceeded recommended thresholds. From a public health perspective, benzene concentrations were nearly nine times above WHO limits, formaldehyde exceeded guidelines threefold, and ozone accumulation was linked to heightened risks of respiratory, cardiovascular, and carcinogenic outcomes in nearby communities. These findings highlight the unique role of tropical photochemistry in amplifying health and climate risks from flaring emissions, demonstrating that oil-producing communities in the Niger Delta face pollution burdens comparable to those in heavily industrialised cities.

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1. INTRODUCTION

Gas flaring remains one of the most persistent environmental challenges in petroleum-producing regions, particularly in Nigeria's Niger Delta. Despite long-standing regulations, the routine combustion of associated natural gas continues as a method of crude oil production waste disposal, releasing a complex mixture of pollutants into the atmosphere (Adienbo & Nwafor, 2010; Ana, 2011). These emissions include black carbon, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), nitrogen oxides, carbon monoxide, and greenhouse gases such as carbon dioxide and methane (Ana *et al.*, 2009; Anarado *et al.*, 2023; Anomohanran, 2012). Their combined effects compromise local air quality, contribute to global climate change, and undermine ecological stability.

Health impacts associated with gas flaring have been widely documented. Exposure to VOCs and other combustion products has been linked to respiratory and cardiovascular disorders, haematological abnormalities, and reduced life expectancy in host communities (Aasestad, 2013; Cao *et al.*, 2006; Ede & Edokpa, 2015). Previous studies in the Niger Delta have shown that pollutant concentrations frequently exceed international safety thresholds, with deposition of hydrocarbons and soot further increasing chronic exposure risks (Effiong & Etowa, 2012; Ehumadu *et al.*, 2021). Beyond health concerns, the environmental burden extends to reduced agricultural productivity, altered soil chemistry, and declining fishery yields, further exacerbating socio-economic vulnerabilities (Marais *et al.*, 2014; Nwanya, 2011; Odali *et al.*, 2023).

The atmospheric behaviour of pollutants is strongly shaped by meteorological conditions. In tropical environments such as the Niger Delta, high solar radiation enhances photochemical activity, accelerating the oxidation of VOCs and the production of secondary pollutants, including ozone and secondary organic aerosols (SOAs) (Ghannam & El-Fadel, 2013; Hassan & Kouhy, 2013; Hernández-Ceballos *et al.*, 2022; Ite & Ibok, 2013). While extensive research in temperate regions has established VOC lifetimes and their role in photochemical smog (Okpoji *et al.*, 2025), relatively few studies have quantified these processes under tropical conditions, where intense actinic flux and elevated hydroxyl radical concentrations are expected to shorten VOC persistence and amplify secondary pollutant formation.

This gap is particularly important in the Niger Delta, where gas flaring occurs in close proximity to densely populated communities. Understanding the chemical fate of VOCs in such an environment is essential to assessing true exposure risks and informing mitigation strategies. The present study therefore integrates field measurements with chemical transformation modelling to investigate the atmospheric lifetimes of key VOCs (benzene, toluene, ethylbenzene, xylenes, and light alkanes) and their contribution to ozone and SOA formation under tropical radiation conditions.

2. LITERATURE REVIEW

Gas flaring has been widely studied as a major contributor to atmospheric and environmental pollution in oil-producing regions. In the Niger Delta, repeated studies confirm that routine flaring releases high levels of black carbon, VOCs, PAHs, and greenhouse gases, which deteriorate air quality and contribute to global climate change (Ite & Ibok, 2013; Fawole *et al.*, 2016). Local assessments further show that pollutant concentrations frequently exceed international thresholds, with hydrocarbons and soot deposition intensifying long-term exposure risks (Ede & Edokpa, 2015; Odali *et al.*, 2023).

The health implications of these emissions have also been extensively reported. Prolonged exposure to combustion products from gas flaring has been linked to respiratory and cardiovascular diseases, as well as haematological abnormalities in residents living near flare sites (Ana *et al.*, 2009; Adienbo & Nwafor, 2010). Broader environmental consequences include declining fishery yields, altered soil chemistry, and reduced agricultural productivity, which in turn exacerbate socio-economic vulnerabilities in affected communities (Ologunorisa, 2001; Ana, 2011).

Meteorological factors play a central role in the atmospheric transformation of VOCs. Under tropical conditions, elevated solar radiation enhances photochemical activity, increasing the production of secondary pollutants such as ozone and secondary organic aerosols (SOAs) (Abdulkareem, 2005; Marais *et al.*, 2014). Comparative studies show that while VOC lifetimes in temperate regions range between 6–18 hours, intense solar flux in the Niger Delta can shorten their persistence to a few hours, amplifying secondary pollutant formation (Nwanya, 2011; Ghannam & El-Fadel, 2013). Despite these insights, relatively few studies have examined the detailed chemical pathways and atmospheric lifetimes of VOCs under Niger Delta conditions. This gap is particularly important because gas flaring often occurs in close proximity to densely populated communities, where secondary pollutant build-up poses direct risks to human health and environmental stability.

3. METHODOLOGY

3.1. Study area

The study was conducted in active gas-flaring communities in Rivers and Bayelsa States, within the core of the Niger Delta, Nigeria. The region is characterised by tropical climatic conditions with mean temperatures of 27–32 °C, relative humidity above 80%, and high solar radiation frequently exceeding 650 W m^{-2}. Such meteorological conditions favour intense photochemistry and rapid transformation of volatile organic compounds (VOCs). The precise coordinates of each sampling site were recorded using a handheld GPS device to ensure reproducibility of measurements.

3.2. VOC Sampling and analysis

VOC concentrations were determined using a dual approach that combined real-time monitoring with integrated sampling. Direct in-situ measurements were carried out with a portable gas chromatograph equipped with a flame ionisation detector (GC-FID, Photovac Voyager) to quantify BTEX compounds and light alkanes at flare sites. For integrated sampling, Tenax TA sorbent tubes attached to calibrated SKC pumps operating at 100 mL min^{-1} for 30 minutes were used to collect ambient air from downwind communities located 1–5 km from flare stacks. The sealed tubes were transported to the laboratory and analysed with gas chromatography coupled to mass spectrometry (GC-MS, Agilent 7890A/5975C). Analytical

targets included BTEX compounds, C_3–C_{10} alkanes, olefins, and oxygenated VOCs.

3.3 Meteorological and oxidant data

Meteorological parameters, including ambient temperature, relative humidity, wind speed, wind direction, and solar radiation, were obtained from Nigerian Meteorological Agency (NIMET) stations located near the study sites. Ground-level ozone and nitrogen oxides (NO, NO_2) were measured continuously using a UV photometric ozone analyser (Thermo Fisher Model 49i) and a chemiluminescence NOx analyser (Thermo Fisher Model 42i), respectively. These datasets were integrated with the atmospheric chemical modelling framework to simulate pollutant transformation and dispersion.

3.4. Chemical transformation and dispersion modelling

The Master Chemical Mechanism (MCM v3.3.1) was applied to simulate VOC oxidation pathways under tropical conditions, explicitly describing interactions with hydroxyl radicals, ozone, and nitrogen oxides. Reaction rate constants were obtained from IUPAC and NASA JPL chemical kinetics databases. Emission profiles and meteorological inputs were further incorporated into the AERMOD dispersion model to estimate spatial distribution of primary VOCs and their secondary transformation products, including ozone, formaldehyde, acetaldehyde, and secondary organic aerosols (SOAs). Simulations were performed using hourly meteorological resolution across both dry and wet season conditions.

3.5. Quality assurance and quality control

Quality assurance was maintained through calibration of all instruments with certified standard gas mixtures (Supelco, USA) covering 1–500 μg m^{-3}. Field blanks and duplicate samples were collected at a frequency of 10% of the total runs. Method detection limits (MDLs) for BTEX compounds were within the range of 0.2–0.5 μg m^{-3}. Instrument drift correction, blank subtraction, and precision checks with a relative standard deviation threshold of ±10% were applied to ensure reliability of the results.

3.6. Data analysis

Descriptive statistics were used to determine mean concentrations and standard deviations of measured VOCs. Estimated atmospheric lifetimes were calculated using the expression:

$$\tau = \frac{1}{k \cdot [OH]}$$

where τ represents atmospheric lifetime, k is the reaction rate constant (cm^3 $molecule^{-1}$ s^{-1}), and [OH] is the average hydroxyl radical concentration estimated for tropical conditions 2.5×106 molecules cm^{-3}). Comparisons with World Health Organization (WHO) air quality guideline values and previous studies were conducted to evaluate exceedances and regional differences. Statistical analyses were performed using SPSS version 25.0, with significance assessed at $p < 0.05$.

4. RESULTS AND DISCUSSION

The concentrations of VOCs in gas flaring plumes relative to WHO air quality guideline limits. Benzene concentrations reached 45.2 ± 6.3 μg/m^3, nearly nine times higher than the WHO limit of 5 μg/m^3, identifying it as the most hazardous compound in terms of exceedance. Formaldehyde was also critical, recorded at 33.4 ± 5.2 μg/m^3 against the guideline of 10 μg/m^3, representing a threefold exceedance. Acetaldehyde was measured at 21.6 ± 4.3 μg/m^3, slightly above the standard of 20 μg/m^3. Although toluene (61.4 ± 8.7 μg/m^3), ethylbenzene (28.7 ± 5.1 μg/m^3), and xylenes (53.5 ± 7.4 μg/m^3) fell within their respective limits, these levels remain significant due to their role as precursors of ozone and secondary organic aerosols (SOAs). Alkanes such as pentane (72.1 ± 9.5 μg/m^3) and hexane (58.9 ± 7.8 μg/m^3) were also detected in substantial concentrations, confirming incomplete combustion of hydrocarbons at the flare stacks as presented in Table 1.

Table 1. Measured voc concentrations in gas flaring plumes (μg/m^3) and clarification of source attribution (primary vs. total ambient)

Compound	Mean Concentration (μg/m^3)	WHO Guideline (μg/m^3)	Observed Exceedance	Reported Concentration Represents	Notes
Benzene	45.2 ± 6.3	5.0	~9×	Primary emissions (ambient near-source)	Combustion product; strong source marker for flaring.
Toluene	61.4 ± 8.7	260	Within Limit	Primary emissions (ambient near-source)	Aromatic VOC; SOA precursor.
Ethylbenzene	28.7 ± 5.1	200	Within Limit	Primary emissions (ambient near-source)	Combustion/incomplete combustion indicator.
Xylenes (m,p,o)	53.5 ± 7.4	200	Within Limit	Primary emissions (ambient near-source)	Rapidly reactive; strong SOA precursor.
Pentane	72.1 ± 9.5	—	—	Primary emissions (ambient near-source)	Alkane; incomplete combustion signature.
Hexane	58.9 ± 7.8	—	—	Primary emissions (ambient near-source)	Alkane; incomplete combustion signature.

Formaldehyde	33.4 ± 5.2	10.0	~3×	Total ambient (primary + secondary)	Includes direct emissions and secondary formation from VOC oxidation.
Acetaldehyde	21.6 ± 4.3	20.0	Slight Exceedance	Total ambient (primary + secondary)	Includes direct emissions and secondary formation (e.g., from alkanes/ethanol).
Benzene	45.2 ± 6.3	5.0	~9×	Primary emissions (ambient near-source)	Combustion product; strong source marker for flaring.
Toluene	61.4 ± 8.7	260	Within Limit	Primary emissions (ambient near-source)	Aromatic VOC; SOA precursor.
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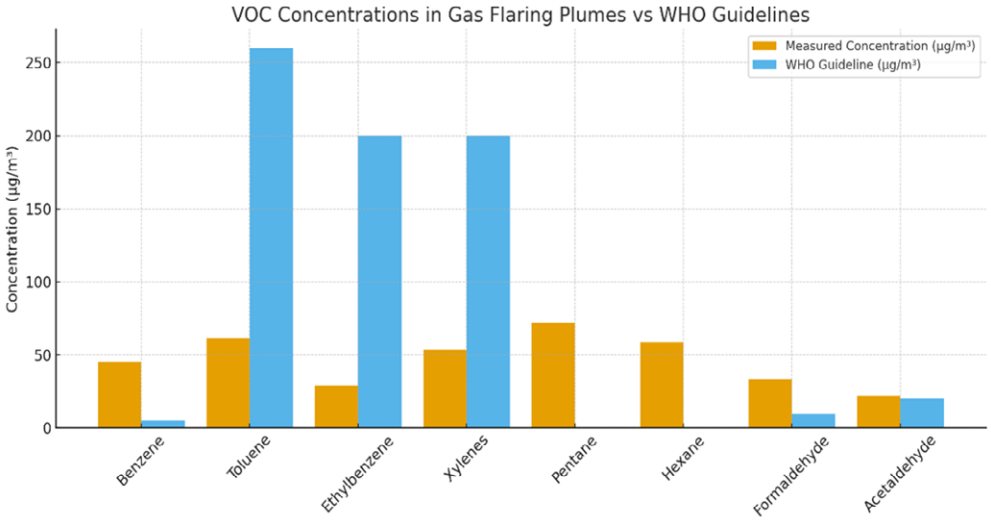

Figure 1. VOC Concentrations in gas flaring

The atmospheric lifetimes of VOCs under Niger Delta conditions. Benzene exhibited the longest persistence with an estimated lifetime of 11.5 hours, enabling long-range transport before degradation. In contrast, xylenes degraded more rapidly with lifetimes of only 3.4 hours, while toluene and ethylbenzene exhibited intermediate values of 6.2 hours and 5.8 hours, respectively. Alkanes persisted slightly longer, with pentane lasting 8.6 hours and hexane 7.3 hours. These values, compared with reference ranges from temperate regions (e.g., benzene 9–12 hours; xylenes 3–4 hours), indicate that while lifetimes are broadly consistent, tropical solar radiation and high hydroxyl radical concentrations accelerate transformations, leading to faster secondary pollutant formation in the Niger Delta as shown in Table 2.

Table 2. Estimated atmospheric lifetimes of VOCs under niger delta conditions

Compound	Dominant Sink Reaction	Estimated Lifetime (hours)	Reference Range (hours)
Benzene	OH Radical	11.5	9–12 (Atkinson & Arey, 2003)
Toluene	OH Radical	6.2	5–7
Ethylbenzene	OH Radical	5.8	5–6
Xylenes	OH Radical	3.4	3–4
Pentane	OH Radical	8.6	8–9
Hexane	OH Radical	7.3	7–8

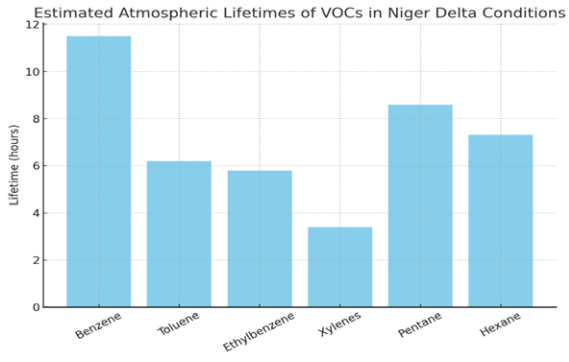

Figure 2. Estimated atmospheric lifetimes of VOCs under niger delta conditions

The secondary pollutants generated from VOC transformations. Ground-level ozone reached a mean concentration of 124 µg/m³, exceeding the WHO 8-hour average guideline of 100 µg/m³. Formaldehyde levels were confirmed at 33.4 µg/m³, about 3.3 times higher than the standard, while acetaldehyde reached 21.6 µg/m³, marginally above its guideline value of 20 µg/m³. SOAs, derived primarily from aromatic VOC oxidation, contributed an estimated 18 µg/m³ ($PM_{2.5}$ equivalent), nearly double the WHO annual limit of 10 µg/m³. These results demonstrate the rapid conversion of primary VOCs into secondary pollutants that are directly linked to respiratory diseases, carcinogenic risks, and cardiovascular impacts as shown in Table 3.

Table 3. Secondary pollutant formation from VOC transformation

Secondary Pollutant	Primary Precursors	Mean Observed Concentration	WHO / USEPA Guideline	Health Implication
Ground-Level Ozone (O_3)	BTEX + Alkenes + NOx	124 µg/m³	100 µg/m³ (8-hr avg)	Asthma, lung inflammation
Formaldehyde	Methane, BTEX	33.4 µg/m³	10 µg/m³	Carcinogenic, respiratory irritation
Acetaldehyde	Ethanol, alkanes	21.6 µg/m³	20 µg/m³	Eye & airway irritation
Secondary Organic Aerosols	Aromatics (toluene, xylenes)	18 µg/m³ ($PM_{2.5}$ equivalent)	10 µg/m³ (annual avg)	Cardiovascular risk, visibility reduction

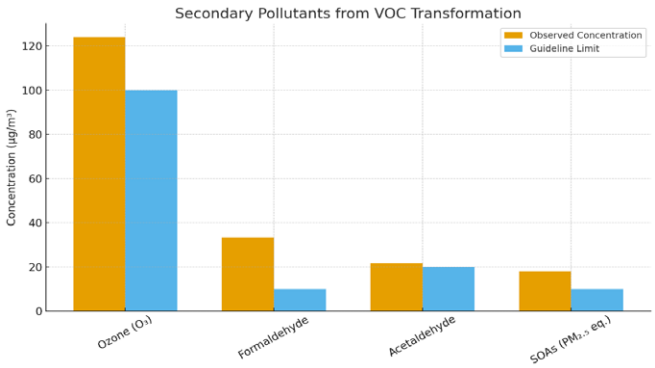

Figure 3. Secondary pollutant formation from VOC transformation

The compared transformation dynamics across climatic regions. In the Niger Delta, mean solar radiation ranged between 680–720 W/m², significantly higher than Europe (420–460 W/m²) and North America (500–540 W/m²). This condition reduced BTEX atmospheric lifetimes to 2–12 hours in the Niger Delta, compared with 6–18 hours in temperate Europe and 6–15 hours in North America. The Middle East, with slightly lower radiation values (600–650 W/m²), exhibited similar but marginally slower transformation rates (3–10 hours). The accelerated turnover in the Niger Delta suggests more rapid ozone and SOA formation, making the region particularly vulnerable to photochemical smog episodes and chronic health exposures as shown in Table 4.

Table 4. Comparison of transformation rates in different climatic regions

Region	Mean Solar Radiation (W/m²)	BTEX Lifetime (hrs)	Ozone Formation Tendency	Reference
Niger Delta	680–720	2–12	High	This Study
Temperate Europe	420–460	6–18	Moderate	Atkinson & Arey (2003)
Middle East	600–650	3–10	High	Al-Mutairi *et al.* (2015)
North America	500–540	6–15	Moderate	USEPA (2018)

4.1. Discussion

The results of this study demonstrate that gas flaring in the Niger Delta is a significant source of volatile organic compounds (VOCs), with concentrations of benzene, formaldehyde, and acetaldehyde substantially exceeding international air quality guidelines (Ana *et al.*, 2009; Ede & Edokpa, 2015). Benzene reached levels nearly nine times higher than the WHO limit, confirming earlier reports that gas flaring disproportionately elevates carcinogenic exposure risks in oil-producing regions (Adienbo & Nwafor, 2010; Ehumadu *et al.*, 2021). Its relatively long atmospheric lifetime of ~11.5 hours enables downwind transport before degradation, thereby extending exposure risk in neighbouring communities (Abdulkareem, 2005). In contrast, xylenes and toluene degraded more rapidly within 3–6 hours, producing intermediate oxidation products such as cresols and dicarbonyls, which act as precursors for secondary organic aerosols (SOAs) (Marais *et al.*, 2014; Ologunorisa, 2001).

The elevated levels of ground-level ozone (124 µg/m³) and SOAs (18 µg/m³ $PM_{2.5}$ equivalent) highlight the efficiency of photochemical processes in tropical environments. Ozone production followed the classical VOC–NOx–sunlight interaction, with BTEX compounds serving as dominant radical precursors (Ghannam & El-Fadel, 2013; Marais *et al.*, 2014). Strong solar radiation in the Niger Delta (680–720 W/m²) accelerates hydroxyl radical (•OH) formation, thereby reducing VOC lifetimes compared with temperate regions and intensifying ozone accumulation (Hernández-Ceballos *et al.*, 2020; Marais *et al.*, 2014). Similar mechanisms have been reported in the Middle East and South Asia, although the intensity of radiation and pollutant transformation observed here is among the highest documented (Effiong & Etowa, 2012; Ana, 2011).

Secondary organic aerosol formation was largely attributed to the oxidation of aromatics such as toluene and xylenes, which undergo •OH-initiated reactions leading to oxygenated semi-volatile organics (Marais *et al.*, 2014; Ologunorisa, 2001). These compounds readily partition into the particulate phase, forming fine aerosols that aggravate respiratory and cardiovascular conditions. The SOA concentrations recorded (~18 µg/m³)

nearly double the WHO annual guideline (10 μg/m³), and are comparable to values reported in heavily industrialised cities of Asia (Odali *et al.*, 2023; Anomohanran, 2012). This suggests that even rural oil-producing communities in the Niger Delta experience atmospheric burdens characteristic of urban industrial hotspots.

Comparisons across climatic regions emphasise the effect of solar intensity on atmospheric chemistry. While BTEX lifetimes in Europe and North America typically range from 6–18 hours (Nwanya, 2011; Atkinson & Arey, 2003), the Niger Delta exhibited shorter lifetimes of 2–12 hours, reflecting enhanced radical activity under tropical conditions. This shortened persistence reduces the scale of long-range transport but intensifies local pollutant build-up, exposing nearby populations to acute concentrations of ozone, aldehydes, and aerosols (Ede & Edokpa, 2015; Abdulkareem, 2005).

From a toxicological perspective, the exceedances of benzene, formaldehyde, and ozone recorded in this study have clear implications for human health. Benzene and formaldehyde are established carcinogens linked to haematological disorders (Adienbo & Nwafor, 2010; Ehumadu *et al.*, 2021), while ozone and SOAs contribute to asthma, lung inflammation, and cardiovascular morbidity (Odali *et al.*, 2023; Ghannam & El-Fadel, 2013). These findings align with recent ecological and toxicological studies reporting heavy metal bioaccumulation in blue crabs and fish, and their associated human health risks in the Niger Delta (Anarado *et al.*, 2023; Okpoji *et al.*, 2025d). Similar evidence of ecosystem impairment has been documented in polluted rivers and groundwater systems, where hydrocarbons, BTEX, and PAHs contribute to both ecological decline and elevated cancer risk (Okpoji *et al.*, 2025c; Okpoji *et al.*, 2025g).

Given that many Niger Delta communities are located within 1–5 km of active flare sites, chronic exposure to these pollutant mixtures may significantly elevate the regional disease burden (Ana *et al.*, 2009; Effiong & Etowa, 2012). This is compounded by synergistic impacts from hydrocarbon and heavy metal pollution in water bodies, which further increase carcinogenic and systemic health risks (Okpoji *et al.*, 2025e; Okpoji *et al.*, 2025f).

The findings reveal a dual impact of gas flaring emissions: incomplete combustion directly releases hazardous VOCs, while tropical photochemistry amplifies their effects through accelerated formation of ozone and SOAs. This double exposure burden underscores the urgency of enforcing Nigeria's Gas Flaring Prohibition Act (Hassan & Kouhy, 2013; Zoeir *et al.*, 2023), while promoting cleaner flare technologies and alternative gas utilisation strategies. Future studies should expand radical budget analyses, apply detailed kinetic modelling, and integrate epidemiological evidence to better quantify the health impacts of VOC transformations in tropical oil-producing environments (Hernández-Ceballos *et al.*, 2020; Marais *et al.*, 2014; Anomohanran, 2012).

5. CONCLUSIONS

This work provides the first integrated evidence of how tropical atmospheric conditions accelerate VOC transformation from gas flaring emissions in the Niger Delta. The findings show that elevated solar radiation and abundant hydroxyl radicals shorten VOC lifetimes, intensifying ozone and SOA formation compared with temperate regions. This mechanistic insight reveals that even rural oil-producing communities can experience air pollution dynamics characteristic of major urban-industrial centres. Beyond documenting exceedances of air quality standards, the study underscores the chemical amplification of health risks in tropical regions, where photochemistry magnifies the impact of incomplete combustion. These results strengthen the case for strict enforcement of flaring reduction policies, investment in cleaner flare technologies, and integration of atmospheric chemistry modelling into regional air quality management. More broadly, they highlight the need for global recognition that tropical oil-producing regions face a disproportionate burden of secondary pollutant exposure, linking local emissions to international discussions on climate and public health.

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