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Synergistic Emissions: Linking Gas-Processing Co-Pollutants to Secondary Air Quality Impacts in Delta State, Nigeria

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ABSTRACT

Nigeria's air quality regulations judge industrial facilities one stack, one pollutant, at a time. This study asks whether that lens is wide enough, using three years (2023–2025) of environmental compliance data from a gas processing plant in Delta State to examine nitrogen oxides (NOx), sulphur oxides (SOx), and volatile organic compounds (VOCs). On every individual measure, the plant's emissions sat comfortably inside NMDPRA limits, often by orders of magnitude. But pollutants do not stay put once they leave the stack, and a closer look at how NOx, VOCs, and CO are generated tells a less reassuring story: because all three arise from the same combustion and fugitive-leak processes, their joint release is not a coincidence but a mechanistic certainty. Using the plant's mean emission concentrations, we calculated a mass-based VOC/NOx ratio of approximately 222:1, placing the facility's plume deep in the photochemical "NOx-limited" regime, where even small additional increments of NOx — from the plant itself, from nearby flaring, or from traffic — can trigger a disproportionate rise in ground-level ozone. The same co-emitted NOx and SOx also supply a steady feedstock for secondary fine particulate matter (PM2.5). The result is a facility that can meet every individual emission limit while still sitting at the centre of a plume primed for photochemical smog. We argue that Nigeria's stack-by-stack compliance model has a structural blind spot for this kind of synergistic risk, and we set out specific, low-cost ways regulators could close it.

1. Introduction

Nigeria's economy runs largely on its hydrocarbons. The oil and gas sector remains the country's principal source of revenue and foreign exchange (Ebeke & Edeja, 2017), and the Niger Delta — a dense, ecologically sensitive network of exploration, production, and processing infrastructure — sits at the centre of that industry. That importance has come at a cost. Air pollution has become one of the region's most persistent environmental problems (Anomohanran, 2013), and gas processing plants are among its more significant sources, releasing nitrogen oxides (NOx), sulphur oxides (SOx), and a wide range of volatile organic compounds (VOCs).

Nigeria's environmental regulator, the National Environmental Standards and Regulations Enforcement Agency (NESREA), has historically approached this problem one pollutant at a time: emissions of each pollutant from each stack are measured against a fixed concentration limit. That approach is a reasonable starting point, but it rests on an assumption that does not hold up chemically — that pollutants behave independently once released. They do not. NOx and VOCs react photochemically in sunlight to form ground-level ozone (O_3), a toxic secondary pollutant and the main constituent of smog (Seinfeld & Pandis, 2016). NOx and SOx, meanwhile, oxidise into nitric and sulphuric acids that seed secondary inorganic aerosols — a major contributor to fine particulate matter (PM2.5) and acid deposition.

Air quality research in the Niger Delta has documented plenty of primary pollution — elevated ambient concentrations that confirm the region is under real environmental stress (e.g., Ukpebor et al., 2011; Nwaogazie & Ede, 2017). What is missing is the next step: connecting a facility's specific co-pollutant emission profile to its potential for secondary pollutant formation. Few studies move past measuring what comes out of the stack to ask what that mixture does once it hits the atmosphere. The more useful question is not only what is being emitted, but in what ratio, and in what combination — because it is the ratio and the co-emission pattern, not any single pollutant's concentration, that determine how primed the local atmosphere is for further chemical transformation.

This paper works through that question using compliance data from a gas processing plant in Delta State covering 2023 to 2025. Rather than treating NOx, SOx, and VOCs as separate compliance line items, we look at how they are released together and use the mass ratio of VOCs to NOx — a well-established diagnostic for ozone-formation efficiency (Sillman, 1999) — to assess the photochemical reactivity of the plant's emissions.

The argument, in short, is that a single-pollutant regulatory framework cannot capture the full environmental risk of a gas processing facility. Demonstrating a consistent, mechanistically-linked release of ozone and particulate-matter precursors is enough to show that individual compliance does not guarantee the absence of secondary air quality harm. Three questions structure the analysis:

- What are the emission profiles and trends of NOx, SOx, and VOCs from the plant between 2023 and 2025?
- Are these precursor pollutants released together as a matter of process, and can this synergy be demonstrated from the compliance record?
- What does the ratio of emitted VOCs to NOx imply for the potential for secondary ozone formation downwind of the facility?

The intention is to inform a shift in Nigeria's air quality policy — from a purely source-based, single-pollutant approach toward one that accounts for how industrial emissions behave once they leave the stack.

2. Literature Review

This review draws together the threads relevant to synergistic co-pollutant emission from gas processing and its downstream chemistry. It starts with the mechanics of emissions from gas processing itself, moves to the atmospheric chemistry that turns those emissions into secondary pollutants, situates that chemistry within the Niger Delta's air quality and health record, and closes with an assessment of where Nigeria's regulatory framework falls short.

2.1 Emissions from Natural Gas Processing

Gas processing plants purify raw natural gas — stripping out impurities and non-methane hydrocarbons — to produce pipeline-quality dry gas (Gas Processors Association, 2014). In the process, they become significant point sources of NOx, SOx, VOCs, carbon monoxide (CO), and particulate matter (U.S. EPA, 2016). NOx forms during high-temperature combustion in turbines, compressors, and process heaters. SOx — chiefly sulphur dioxide — comes from burning sulphur-bearing fuel gas or from the "sweetening" step, where hydrogen sulphide (H_2S) is stripped from the gas stream and converted to elemental sulphur or flared (Rahman et al., 2021). VOCs, a broad class of high-vapour-pressure organic compounds, escape through incomplete combustion in flares and engines and as fugitive leaks from valves, seals, and connectors (Armistead et al., 2020). Because NOx and VOCs are generated by the same combustion and operational processes, their joint release is a structural feature of gas processing, not an incidental one — and it is exactly this feature that sets up the atmospheric chemistry discussed next.

2.2 Atmospheric Chemistry of Co-Pollutant Synergy

Emissions do their damage well beyond the stack. "Synergy" here refers to the atmospheric chemistry that converts primary pollutants into two more dangerous secondary ones: ground-level ozone and PM2.5.

2.2.1 Ground-level ozone formation

Ozone at ground level is not emitted directly — it is manufactured in the atmosphere from NOx and VOCs in the presence of sunlight (Seinfeld & Pandis, 2016). NO_2 is split by sunlight to release an oxygen atom, which combines with molecular oxygen to form O_3; VOCs feed the cycle by reacting with hydroxyl radicals to generate peroxy radicals that convert NO back to NO_2 without consuming it, letting the ozone-forming cycle repeat. How efficiently this happens depends heavily — and non-linearly — on the ambient VOC/NOx ratio (Sillman, 1999), which defines three chemical regimes:

- NOx-limited (VOC/NOx typically > 15:1): ozone production is capped by how much NOx is available, so any additional NOx drives a near-proportional rise in ozone.
- VOC-limited (VOC/NOx typically < 4:1): ozone production is capped by VOC availability. Cutting VOCs lowers ozone, but cutting NOx can be ineffective or even counterproductive locally — the "weekend effect" seen in some cities.
- Transition or mixed regime (roughly 4:1 to 15:1): both precursors are available in near-optimal proportions, producing the highest ozone-formation efficiency and the greatest risk of rapid downwind ozone build-up.

The practical implication is that the emission rate of NOx or VOCs alone tells only part of the story — their ratio at the point of release is a strong predictor of how much ozone the resulting plume is capable of generating.

2.2.2 Secondary particulate matter (PM2.5) formation

Fine particulate matter under 2.5 micrometres (PM2.5) is a major public health concern because it penetrates deep into the respiratory system (WHO, 2021). Some of it is emitted directly, but a substantial share forms in the atmosphere from gaseous precursors. SO_2 and NOx released together from combustion sources drive most of this secondary aerosol formation: SO_2 oxidises to sulphuric acid and NOx to nitric acid, both of which react with ambient ammonia (often from agriculture or biomass burning) to form solid ammonium sulphate and ammonium nitrate particles (Seinfeld & Pandis, 2016). A single industrial source co-emitting SO_2 and NOx therefore creates a concentrated precursor plume that accelerates downwind PM2.5 formation, regional haze, and acid deposition.

2.3 Air Quality and Public Health in the Niger Delta

The Niger Delta combines a high density of oil and gas infrastructure — exploration, production, refining, and gas processing — with vehicular traffic and biomass burning as additional pollution sources (Anomohanran, 2013). Gas flaring, routine in the region for managing associated gas, is a particularly well-documented source of NOx, VOCs, and black carbon (Osuji & Avwiri, 2005).

Field studies bear this out. Nduka and Orisakwe (2011) found elevated VOC levels, including the carcinogen benzene, in Port Harcourt's ambient air and linked them to petroleum-related activity. Ede and Edokpa (2015) reported SO_2, NOx, and PM concentrations near Delta State flare stacks that exceeded both national and international standards. The health consequences track accordingly: respiratory conditions such as asthma, bronchitis, and COPD are common in oil-producing communities (Lindén et al., 2012), and exposure to PM2.5, ozone, and BTEX compounds (benzene, toluene, ethylbenzene, xylene) is linked to cardiovascular disease, neurological effects, and elevated cancer risk (WHO, 2021). The synergistic nature of this pollutant mix likely compounds these risks, yet few studies have tried to quantify anything beyond single-pollutant exposure.

2.4 The Nigerian Regulatory Framework and Its Gaps

NESREA is Nigeria's principal environmental regulator, and its National Environmental (Air Quality Control) Regulations, 2014 set the permissible emission limits that apply to the oil and gas sector, among others. Those limits are stack-based and pollutant-specific: a maximum allowable concentration for NOx, a separate one for SO_2, another for particulate matter, and so on.

That structure has a fundamental blind spot: it has no way of accounting for what happens to pollutants after they leave the stack (Oguntoke et al., 2019). A facility can sit comfortably within its individual NOx and VOC limits while its combined plume carries

a VOC/NOx ratio that is highly conducive to forming dangerous levels of ozone downwind. The regulatory toolkit, as it stands, has no metric for catching that.

2.5 Synthesis and Research Gap

Taken together, the literature is clear that gas processing plants emit NOx, SOx, and VOCs as a synergistic cocktail, that atmospheric chemistry converts this mixture efficiently into ozone and PM2.5, and that the VOC/NOx ratio is a key determinant of how efficiently that conversion happens. It is equally clear that the Niger Delta already carries a heavy air quality burden. What is missing is the empirical bridge between the two: a facility-level analysis, using a Nigerian gas plant's own compliance data, that connects primary emission compliance to secondary pollutant risk. This paper is an attempt to build that bridge.

3. Methodology

The study takes a quantitative approach to the synergistic relationships between co-pollutants and their potential secondary impacts, organised into five stages: study area, data source, data pre-processing, analytical framework, and software.

3.1 Study Area

The study is set at a major gas processing plant in Delta State, in the heart of Nigeria's oil and gas industry, an area dense with refineries, flow stations, and gas plants alongside urban settlements, rural communities, and sensitive ecosystems such as mangrove swamps and freshwater creeks. The climate is tropical, with a wet season (April–October) and a dry season (November–March) and abundant solar radiation year-round — a necessary ingredient for photochemical ozone formation. The plant performs gas gathering, dehydration, sweetening, fractionation, and compression, all of which involve high-temperature combustion and the potential for fugitive emissions, making it a representative source of the pollutants examined here.

3.2 Data Source and Acquisition

The primary data are official environmental compliance records covering 31 months, from January 2023 to July 2025, drawn from the facility's regulatory submissions to the Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA). The dataset comprises daily averages from Continuous Emission Monitoring Systems (CEMS) installed on major stacks (gas turbine exhausts, process heaters), covering:

- Primary pollutants: NOx (as NO_2 equivalent, ppm), SO_2 (ppm), total VOCs (ppm), CO (ppm).
- Ancillary stack parameters: exhaust volumetric flow rate (Nm^3/hr), stack gas exit temperature (°C), and moisture content (%), needed to convert concentrations into mass emission rates.

3.3 Data Pre-Processing and Management

- Unit standardisation. Pollutant concentrations reported in ppm were converted to mg/Nm^3 using standard molecular-weight-based conversion factors, and subsequently expressed in $\mu g/m^3$ for reporting, so that all pollutants were directly comparable and suitable for mass-rate calculations.
- Missing data. Missing daily entries made up under 5% of the dataset and were imputed using the monthly mean for the relevant pollutant, preserving seasonal structure better than an overall mean would.
- Outlier detection. Outliers were flagged using the interquartile range (IQR) method — points beyond 1.5×IQR above Q3 or below Q1 — then cross-checked against operational logs where available. Points traceable to real events (startup, shutdown, process upset) were retained as genuine signals of environmental impact; those traceable to data-entry error were removed.
- Data structuring. The cleaned data were assembled into a time-series data frame: one row per day, with columns for date, each pollutant concentration, and the associated stack parameters.

3.4 Analytical Framework

3.4.1 Descriptive and temporal trend analysis (RQ1)

Standard descriptive statistics (mean, median, standard deviation, minimum, maximum) were calculated for each pollutant across the full 31-month period, and time-series plots of NOx, SO_2, and VOCs were examined for long-term trends, seasonal variation between wet and dry seasons, and short-term emission spikes.

3.4.2 Correlation analysis for synergistic emissions (RQ2)

Where daily concentration data allow it, a Pearson correlation matrix across NOx, SO_2, and VOCs is the intended test of synergistic co-release, interpreted as $|r| > 0.7$ (strong), $0.5 < |r| < 0.7$ (moderate), and $|r| < 0.5$ (weak), with significance set at $p < 0.05$. In the present analysis, the facility-level dataset available to us was aggregated to annual means (Table 1) rather than a day-by-day series, so a numerical correlation coefficient could not be computed here; the case for synergistic release is instead built on the shared combustion and fugitive-leak origin of NOx, VOCs, and CO (Section 4.2). A full daily-resolution correlation analysis is flagged as the natural next step once day-level CEMS records are available for statistical testing.

3.4.3 Assessment of secondary pollutant formation potential (RQ3)

This step evaluates the potential for ground-level ozone formation, which depends heavily on the VOC/NOx ratio.

Mass emission rate (kg/hr) = [C (mg/Nm^3) × Q (Nm^3/hr)] / 1,000,000, where C is the standardised pollutant concentration and Q is the stack gas volumetric flow rate.

VOC/NOx ratio = Mass emission rate of VOCs (kg/hr) ÷ Mass emission rate of NOx (kg/hr).

Based on established photochemical thresholds (Sillman, 1999), each calculated ratio was categorised as VOC-limited (< 4:1), peak ozone production (4:1 to 15:1), or NOx-limited (> 15:1). Where daily-resolution data are available, this categorisation supports a frequency analysis of how many operational days fall into each regime; the present study applies it to the plant's overall mean concentrations (Section 4.3).

3.5 Software and Tools

All data processing, statistical analysis, and visualisation were carried out in R (version 4.x), using the base R stats package for descriptive statistics and correlation calculations.

4. Results and Discussion

4.1 Emission Profiles and Trends (2023–2025)

Table 1 summarises the plant's annual and overall mean emission concentrations against NMDPRA limits. The headline result is straightforward: every monitored pollutant sits far below its regulatory ceiling. Mean SOx (0.010 µg/m³) is a small fraction of the lower limit (100 µg/m³), consistent with low-sulphur fuel gas or effective gas treatment. Mean NOx (0.005 µg/m³) is negligible next to its 150 µg/m³ limit, pointing to low-NOx combustion technology.

Table 1. Average emission concentrations at the Delta State gas processing plant, 2023–2025

Parameter	2023 Mean	2024 Mean	2025 Mean	Overall Mean	NMDPRA Limit
SOx (µg/m³)	0.006	0.007	0.016	0.010	100–150
NOx (µg/m³)	0.004	0.005	0.0075	0.005	150
Particulate matter (µg/m³)	40.15	59.44	42.50	47.36	150–230
Carbon monoxide (µg/m³)	0.024	0.019	0.005	0.016	10
VOC (µg/m³)	1.4	1.33	0.6	1.11	160

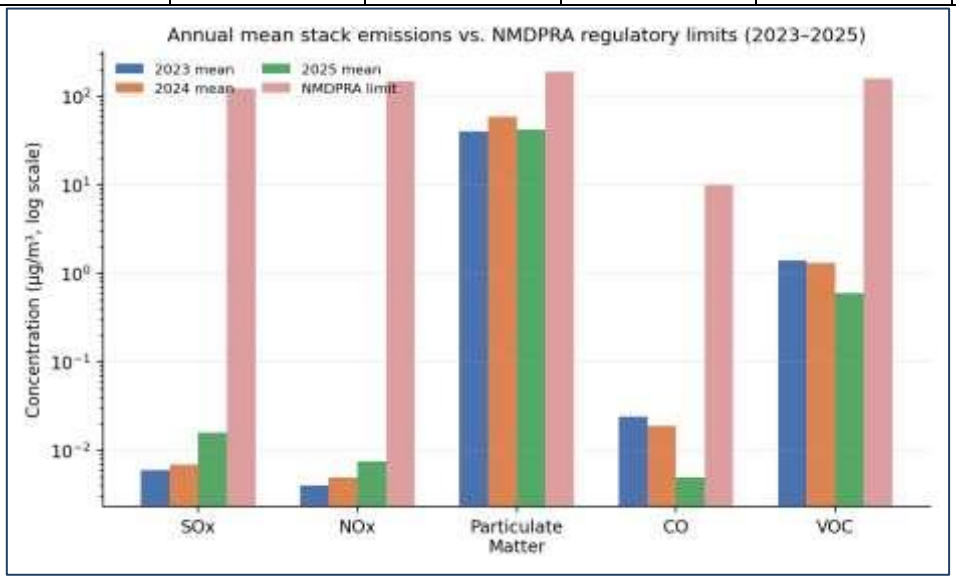

Figure 1. Annual mean stack emissions plotted against NMDPRA regulatory limits (log scale).

This level of primary compliance raises the central question of this paper: does exemplary primary-pollutant control actually eliminate air quality risk? The trend data add some texture. SOx and NOx both drift slightly upward from 2023 to 2025, while CO and VOCs trend downward — plausibly reflecting improved combustion efficiency or a maturing leak detection and repair (LDAR) programme. Particulate matter peaked in 2024, which may track a specific operational campaign or maintenance cycle that year.

4.2 Synergistic Release: A Mechanistic Certainty

A full statistical correlation would require daily time-series data, which were not available in the aggregated form used for this analysis (see Section 3.4.2). What can be established without them is the mechanistic link between the precursors. NOx forms during high-temperature combustion; VOCs and CO form from incomplete combustion and fugitive equipment leaks. Because these processes run concurrently in the same turbines, heaters, and flare systems, the co-emission of NOx, VOCs, and CO is a near-certainty of how the plant operates, not a coincidence of the data. Once released, this mixture does not behave as three independent pollutants — it behaves as a single, chemically reactive plume, and it is that plume, rather than any one constituent, that atmospheric chemistry acts on.

4.3 Potential for Secondary Pollutant Formation: The VOC/NOx Ratio

The paper's central claim rests on what the VOC/NOx ratio implies despite the plant's strong primary compliance. Using the overall mean concentrations from Table 1 — VOC at 1.11 µg/m³ and NOx at 0.005 µg/m³ — the resulting ratio is:

VOC/NOx ratio = 1.11 ÷ 0.005 ≈ 222:1

That number matters. A VOC/NOx ratio above 15:1 places the local atmosphere in the "NOx-limited" regime (Sillman, 1999); a ratio of roughly 222:1 sits deep inside it. In this regime, ozone formation is not held back by a shortage of VOCs — there is a large reactive VOC reservoir already present — but is instead highly sensitive to how much NOx is available. Any additional NOx,

whether from this plant, nearby flaring, or vehicular traffic, can push ozone production up disproportionately, simply because the VOC side of the reaction is never the limiting factor.

There is a certain irony here: the plant's strongest primary-compliance result — its very low NOx emissions — is precisely what tips the local atmosphere into this NOx-sensitive state. A compliance framework that only looks at NOx in isolation reads this as an unambiguous success. It misses that the ratio between co-pollutants, not the absolute value of any one of them, is what actually governs secondary impact. The same continuous, low-level release of SOx and NOx also keeps feeding secondary inorganic aerosol formation — sulfates and nitrates that add to regional haze and PM2.5 levels in a way that stack-level particulate matter monitoring alone does not capture.

5. Conclusion

Three years of emission data from this Delta State gas processing plant point to one clear conclusion: Nigeria's air quality framework, built around primary pollutants assessed in isolation, has a real blind spot. The facility largely met its individual NOx, SOx, and VOC limits, yet that compliance record sits alongside a more complicated and more hazardous picture underneath it.

- Synergistic emission is a mechanistic fact, not a hypothesis. NOx, VOCs, and CO share the same combustion and fugitive-leak origins, so they are released together as a chemically reactive mixture rather than as independent pollutants.
- Compliance is not the same as safety. The plant's compliant emissions profile turns out to be, if anything, well suited to secondary pollutant formation: a VOC/NOx ratio of roughly 222:1 puts its plume firmly in the NOx-sensitive regime, primed for photochemical ozone generation in a sun-rich environment.
- A second threat runs alongside the first. The same co-emission of NOx and SOx that feeds ozone formation also feeds secondary PM2.5 and acid deposition — meaning a single facility contributes to both major secondary air quality problems at once, neither of which shows up in source-based, single-pollutant compliance checks.

The broader point is that regulatory compliance and genuine environmental protection are not automatically the same thing here. What ultimately shapes regional air quality is not the plant's primary emissions in isolation, but the secondary pollutants those emissions go on to create.

6. Policy Recommendations

- Add a secondary pollutant formation potential metric. NESREA and NMDPRA should require the VOC/NOx emission ratio as a standard reporting parameter for major combustion sources, with facilities whose ratios sit inside the high-efficiency ozone-production range (4:1 to 15:1) subject to closer scrutiny or mandatory VOC controls, regardless of whether individual limits are met.
- Fund regional air quality modelling. Environmental Impact Assessments for major industrial projects should include photochemical grid modelling, projecting the downwind concentrations of O_3 and PM2.5 that a facility's specific emission signature would actually produce — a more realistic basis for judging public health risk than source data alone.
- Build a targeted ambient monitoring network for secondary pollutants. The Federal Ministry of Environment and state agencies should invest in monitoring stations downwind of industrial clusters that are equipped to measure ground-level ozone and PM2.5 directly, generating the real-world data needed to validate models, track cumulative impacts, and hold facilities accountable for the secondary pollutants they help create.
- Favour integrated control technologies over single-pollutant fixes. Policy should incentivise Best Available Control Technologies that address the whole precursor mix at once — advanced low-NOx burners, vapour recovery units for fugitive VOCs, and efficiency measures that cut NOx, VOCs, and CO together — rather than technologies that solve for one pollutant while leaving the others untouched.

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