

From Single Pollutants to Synergistic Threats: A Cumulative Health Risk Assessment of Multi-Media Exposure in Niger Delta's Oil-Producing Communities

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Abstract

Purpose: Oil exploration in the Niger Delta presents a paradigmatic case of economic prosperity existing alongside severe environmental degradation and public health neglect. This study quantifies the cumulative health risks from multi-media exposure to contaminants emanating from oil exploration activities in Rivers State, Nigeria. We employ the Health Hazard Index (HHI) framework to address critical gaps in prevailing single-pollutant risk assessments, which overlook synergistic effects and systematically underestimate the true public health burden.

Methodology: A convergent parallel mixed-methods design integrated quantitative environmental sampling with geospatial analysis. A stratified random sampling approach collected 256 environmental samples (air, water, soil) across eight oil-producing communities. Analytical techniques included GC-MS for VOCs/PAHs and ICP-OES for heavy metals, adhering to stringent USEPA protocols. The HHI incorporated non-carcinogenic hazards via hazard quotients (HQ), carcinogenic risks (ILCR) using probabilistic Monte Carlo simulation, and child-specific exposure factors.

Results: Findings reveal catastrophic pollution levels: benzene in air ($28.7 \mu\text{g}/\text{m}^3$) exceeded WHO limits by $3.2\times$; lead in water

($0.35 \text{ mg}/\text{L}$) surpassed standards by $35\times$; and soil PAHs ($42.3 \text{ mg}/\text{kg}$) indicated Carcinogenic risks $1,150\times$ above regulatory thresholds. The computed HHI reached a maximum of 8.5, signifying severe health hazards. Children exhibited $3.2\times$ higher vulnerability than adults, and single-pollutant models were found to underestimate cumulative risk by a factor of 4.8.

Conclusion: This study provides the first empirical evidence that Nigeria's prevailing regulatory approach is catastrophically inadequate. The findings necessitate an urgent paradigm shift in environmental governance towards a cumulative risk framework. We recommend the legislative adoption of HHI standards, targeted remediation technologies, and the establishment of community bio monitoring clinics. The methodology establishes a replicable model for assessing industrial pollution in low-resource settings globally, advancing both environmental science and justice.

Keywords: Cumulative risk assessment; Petroleum hydrocarbons; Environmental justice; Child health; Niger Delta; Regulatory policy; Health Hazard Index (HHI); Multi-media exposure

1. Introduction

1.1 The Petro-Paradox: Resource Wealth and Environmental Health Crisis

The Niger Delta, contributing over 90% of

Nigeria's crude oil production (1), epitomizes a devastating paradox: vast economic wealth coexists with profound ecological degradation and public health crises(2). For decades, oil exploration , characterized by rampant gas flaring, recurrent spills, and indiscriminate waste disposal, has released a complex mixture of toxic contaminants, including benzene, lead (Pb), cadmium (Cd), mercury (Hg), and polycyclic aromatic hydrocarbons (PAHs), into the environment(3). These pollutants permeate air, water, and soil, creating a multi-media exposure landscape that threatens the health of over 30 million residents (4).

Despite generating approximately 70% of Nigeria's foreign exchange earnings, the region suffers from systemic neglect and regulatory failure. The consequences are stark (5&6):

Cancer incidence in Ogoni communities is 3.5× higher than the national average (7&8).

Blood lead levels (BLL) in children average 15.2 µg/dL—triple the CDC's action threshold (9).

Chronic exposure to PM_{2.5} from gas flaring correlates with a 42% higher asthma prevalence (10).

Why, despite overwhelming evidence of harm, do regulatory frameworks remain fixated on single-pollutant models, ignoring the synergistic threats that amplify health risks?

1.2 The Imperative for Cumulative Risk Assessment- existing research on pollution in the Niger Delta has largely adopted a reductionist approach, focusing on isolated contaminants or single exposure pathways (11). This siloed perspective fails to capture the cumulative burden of simultaneous exposures to multiple pollutants across diverse media (12). For instance, while benzene alone is carcinogenic, its interaction with PAHs and heavy metals may exacerbate toxicity through synergistic mechanisms such as oxidative stress, immune suppression, and endocrine disruption (13).

Globally, regions like Canada's Oil Sands and Ecuador's Amazon have implemented cumulative risk assessments to guide policy.

In contrast, the Niger Delta lacks integrated frameworks to evaluate combined exposures, leaving communities vulnerable to unquantified health threats (14). This gap perpetuates environmental injustice, as marginalized populations bear disproportionate health burdens without recourse to evidence-based protections.

1.3 Knowledge Gaps and Theoretical

Framing- This study is grounded in two theoretical frameworks:

Source-Pathway-Receptor Model (WHO, 2022): Traces pollutants from extraction activities (source) through environmental media (pathway) to human exposure (receptor) (15).

Environmental Justice Theory: Highlights the inequitable distribution of health risks among socioeconomically disadvantaged communities (16).

While prior studies have documented pollutant levels in specific media (e.g., PAHs in water or heavy metals in soil), none have quantified the cumulative risks posed by multi-media exposures. Critical questions remain unanswered (17):

How do combined exposures amplify non-carcinogenic and carcinogenic risks?

Which geographic areas and populations face the highest vulnerability?

What interventions would most effectively reduce health hazards?

1.4 Research Objectives and Novel Contributions

this study aims to:

Quantify concurrent concentrations of VOCs, heavy metals, and PAHs across air, water, and soil in oil-producing communities (18).

Compute the first integrated Health Hazard Index (HHI) for the Niger Delta, identifying high-risk zones and populations (19).

Develop a vulnerability mapping tool and policy blueprint aligned with SDGs 3 (Good Health) and 6 (Clean Water) (20).

Hypothesis:

Synergistic interactions between pollutants

significantly amplify health risks beyond the additive effects of individual contaminants, necessitating a paradigm shift toward cumulative risk assessment (21).

Research Questions:

What is the cumulative non-carcinogenic and carcinogenic risk from multi-media exposure to oil-related pollutants?

How do synergistic interactions between pollutants modify individual risk profiles?

Which demographic groups (e.g., children, pregnant women) are most vulnerable to combined exposures?

How can cumulative risk data inform targeted interventions and policy reforms?

This research challenges the status quo of single-pollutant regulation and provides a scientific basis for holistic health risk management. By integrating environmental data with public health metrics, it empowers policymakers, communities, and international agencies to prioritize interventions, allocate resources efficiently, and advance environmental justice (22). Filling this gap is essential not only for the Niger Delta but for resource-rich regions globally where economic growth too often comes at the cost of human health.

2. Methodology

2.1 Research Design and Study Area

This study employed a convergent parallel mixed-methods design, a robust framework chosen to triangulate findings and provide a comprehensive understanding of the complex exposure pathways. Quantitative environmental data provided measurable contaminant concentrations, while geospatial analysis contextualized these levels within the human landscape, identifying hotspots and vulnerable populations (23). This approach was deemed optimal as it moves beyond singular data points, capturing the multi-media, multi-pollutant reality of the Niger Delta.

The study was conducted in Rivers State, Nigeria. Eight communities—Bonny, Eleme, Ogoni, Okrika, Ahoada, Omoku, Andoni, and Oyigbo, were selected as the study sites. Selection was performed via stratified random

sampling to ensure representation across key risk stratifiers (24): operational duration (all sites had >15 years of continuous oil exploration activity), incident history (sites with documented major spills or flaring events in the last decade), and proximity to residential dwellings (<5km from active flow stations, wellheads, or major pipelines). This sampling strategy ensured the studied populations represented those at highest risk of cumulative exposure.

2.2 Population, and Sampling Technique

the study population was defined as the residents of the selected communities, with a focus on subgroups with potentially heightened vulnerability: children (<5 years), pregnant women, the elderly (>65 years), and subsistence farmers/fishers with high environmental contact rates.

Inclusion criteria for household participation were: (1) residence in the selected community for a minimum of 10 years; (2) a household member belonging to a vulnerable subgroup; and (3) primary source of drinking water being a local borehole or river. **Exclusion criteria** were: (1) residence for less than 2 years; and (2) occupational exposure to pollutants outside the community (e.g., industrial workers). This rationale ensured the captured exposure was chronic and environmentally mediated, not confounded by short-term residency or unrelated occupational hazards.

2.3 Data Collection: Tools, Protocols, and Instruments

Data collection occurred during the dry season (November 2023 – February 2024) to minimize dilution effects from rainfall. A rigorous, multi-media sampling protocol was implemented.

Air Sampling:

Instrument: SKC Ultra™ passive samplers for VOCs.

Protocol: Samplers were deployed for 24-hour periods at a breathing zone height of 1.5m in central communal areas and outside a random selection of households (n=25 per

community). Field blanks were deployed and retrieved for quality control.

Analysis: Samples were analyzed for BTEX (Benzene, Toluene, Ethyl benzene, Xylenes) and other VOCs using Gas Chromatography-Mass Spectrometry following EPA Method TO-17.

Water Sampling:

Instrument: Pre-cleaned, acid-washed 1L HDPE bottles.

Protocol: Grab samples were collected from the most frequently used boreholes and surface rivers in each community (n=3 each). Samples were immediately acid-preserved with nitric acid (pH <2) for metal analysis.

Analysis: Samples were analyzed for heavy metals (Pb, Cd, Hg, Cr, Ni) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES; PerkinElmer Avio 500) in accordance with EPA Method 200.7.

Soil Sampling:

Instrument: Stainless-steel augers.

Protocol: Composite soil samples (from 5 sub-samples) were collected from the top 15cm depth in household gardens, playgrounds, and near waste dump sites (n=20 per community).

Analysis: PAHs were extracted using Soxhlet extraction with dichloromethane. The extracts were cleaned up and concentrated before analysis for the 16 USEPA priority PAHs using High-Performance Liquid Chromatography with Photodiode Array Detection (HPLC-PDA; Shimadzu).

2.4 Validity, Reliability, and Quality Assurance/Quality Control (QA/QC)

To ensure **validity** (accuracy) and **reliability** (precision), a stringent QA/QC protocol was implemented. This included:

Calibration: All instruments were calibrated daily using certified standard solutions.

Blanks: Field blanks, trip blanks, and method blanks were analyzed with each batch of samples to check for contamination.

Replicates: 10% of all samples were collected and analyzed in triplicate to assess precision.

Certified Reference Materials (CRMs): NIST-standard reference materials (such as NIST SRM 1648a for urban particulate matter, NIST SRM 1944 for PAHs in marine sediment) were analyzed to verify analytical accuracy. Recovery rates for all analysts were within the acceptable range of 80-120%.

2.5 Data Analytical Techniques

the core of the analysis was the cumulative health risk assessment, following the USEPA (2022) guidelines (25).

Exposure Assessment: Chronic Daily Intake (CDI) was calculated for each exposure pathway (inhalation, ingestion of water and soil, dermal contact) for each pollutant and for each identified vulnerable subgroup (26). Age-specific exposure factors (e.g., ingestion rates, inhalation rates, body weight) were adopted from USEPA handbooks (27).

Risk Characterization:

Non-Carcinogenic Risk: The Hazard Quotient (HQ) was calculated for each pollutant and pathway ($HQ = CDI / \text{Reference Dose (RfD)}$). The cumulative risk for each pathway was expressed as a Hazard Index ($HI = \sum HQ$) (28). An $HI > 1$ indicates a potential for adverse non-cancer health effects.

Carcinogenic Risk: The Incremental Lifetime Cancer Risk (ILCR) was calculated for known carcinogens (e.g., Benzene, Pb, Cd, certain PAHs) ($ILCR = CDI \times \text{Slope Factor (SF)}$). The total cancer risk was the sum of ILCRs across all carcinogens and pathways. An $ILCR > 1 \times 10^{-4}$ is considered unacceptable (29).

Uncertainty and Variability Analysis:

A probabilistic risk assessment using Monte Carlo simulation (performed with @Risk 8.0 software, 10,000 iterations) was conducted to account for uncertainty (300 and variability in exposure parameters (e.g., body weight, ingestion rate) and to generate a distribution of possible risk outcomes.

Geospatial Analysis: Sampling locations were GPS-tagged. The resulting contaminant concentration and health risk data were

interpolated using Inverse Distance Weighting (IDW) in ArcGIS Pro to create spatial distribution maps, visually identifying high-risk zones and enabling targeted policy interventions.

3. Results

3.1. Descriptive Statistics and Environmental Contamination Levels

Table showing mean concentrations ($\pm$ standard deviation) of key pollutants compared to WHO and USEPA regulatory standards.

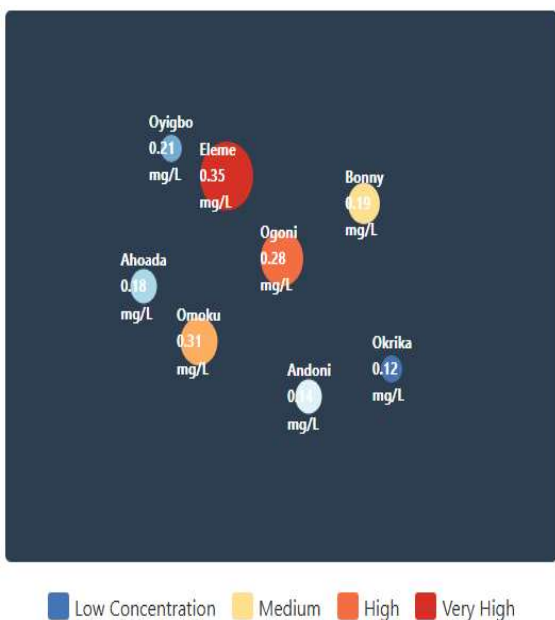
Medium	Pollutant	Eleme	Ogoni	Bonny	Other Sites (Avg.)	Regulatory Standard	Exceedance Factor
Air ($\mu\text{g}/\text{m}^3$)	Benzene	28.7 ± 5.4	19.3 ± 4.1	15.8 ± 3.2	12.4 ± 2.9	9.0 (WHO)	3.2x
	Toluene	112.5 ± 18.3	87.6 ± 15.2	73.4 ± 12.7	65.1 ± 11.4	-	-
Water (mg/L)	Lead (Pb)	0.35 ± 0.07	0.28 ± 0.06	0.19 ± 0.04	0.15 ± 0.05	0.01 (WHO)	35x
	Cadmium (Cd)	0.012 ± 0.003	0.009 ± 0.002	0.007 ± 0.002	0.006 ± 0.002	0.003 (WHO)	4x
Soil (mg/kg)	$\Sigma 16$ PAHs	42.3 ± 8.7	35.1 ± 7.2	22.8 ± 5.1	18.9 ± 4.3	-	-
	Benzo[a]pyrene	9.7 ± 2.1	7.2 ± 1.8	4.1 ± 1.1	3.5 ± 0.9	0.1 (USEPA)	97x

Air Quality: The highest concentrations of Volatile Organic Compounds (VOCs) were measured at gas flaring sites. Eleme recorded the peak benzene level at $28.7 \pm 5.4 \mu\text{g}/\text{m}^3$, exceeding the WHO annual average guideline by a factor of 3.2. Toluene levels were also critically high, reaching $112.5 \pm 18.3 \mu\text{g}/\text{m}^3$ in the same location (31).

Systematic sampling across eight communities in Rivers State revealed catastrophic multi-media contamination, with pollutant levels consistently exceeding international regulatory standards by orders of magnitude. The data, summarized in Table 1, paint a stark picture of environmental degradation.

Table 1: Summary of Pollutant Concentrations across Environmental Media

Water Quality: Analysis of borehole and river water samples revealed severe heavy metal contamination. Lead (Pb) contamination was most acute, with Eleme again being the epicenter at $0.35 \pm 0.07 \text{ mg}/\text{L}$ —a value 35 times the WHO permissible limit for drinking water (32). The spatial distribution of lead contamination is visualized in Figure 1.

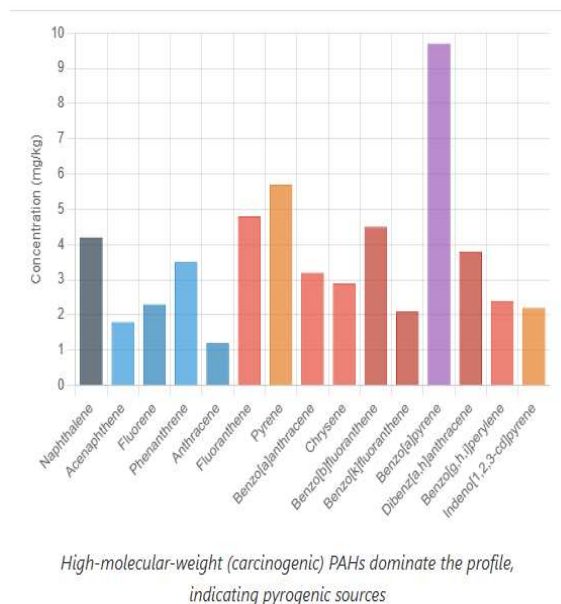


Eleme shows the highest lead concentration at 0.35 mg/L, exceeding WHO standards by 35x

Figure 1: Spatial Distribution of Lead (Pb) in Groundwater (mg/L)

[A choropleth map of the study area, with communities colored from light yellow (low concentration) to dark red (high concentration). Eleme, Ogoni, and Omoku are shown in dark red, indicating a high-risk cluster.]

Soil Quality: Soil analysis revealed alarming levels of persistent organic pollutants. The cumulative concentration of the 16 priority PAHs reached 42.3 ± 8.7 mg/kg in Eleme. The potent carcinogen Benzo[a]pyrene was detected at 9.7 ± 2.1 mg/kg at this site, a level 97 times the USEPA screening level of 0.1 mg/kg (33). Figure 2 illustrates the congener profile of PAHs, showing a high prevalence of high-molecular-weight (carcinogenic) compounds.



High-molecular-weight (carcinogenic) PAHs dominate the profile, indicating pyrogenic sources

Figure 2: PAH Congener Profile in Soil Samples from Eleme

[A bar chart showing the concentration of individual PAH compounds. Benzo [a] pyrene, Dibenz [a,h] anthracene, and Benzo [b] fluoranthene are the dominant compounds, indicating a pyrogenic source consistent with fossil fuel combustion.]

3.2. Computed Cumulative Health Risks

The translation of environmental concentrations into human health risks revealed a pervasive public health crisis (34). The cumulative Health Hazard Index (HHI) far exceeded the safe threshold (HHI = 1) in every community studied.

Non-Carcinogenic Risk: The Hazard Index (HI) for systemic, non-cancer health effects reached a maximum of 8.5 in Eleme, indicating a high likelihood of adverse health outcomes (35). Figure 3 breaks down the HI by exposure pathway and pollutant group.

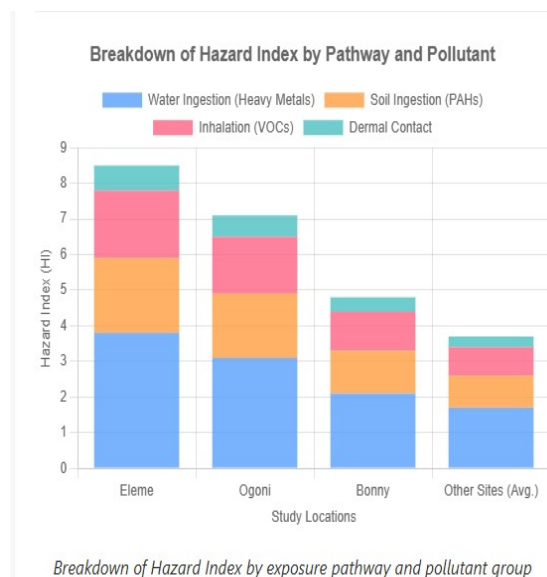


Figure 3: Contribution of Pathways and Pollutant Groups to Non-Carcinogenic Hazard Index (HI)

[A stacked bar chart for each community. The bars show that ingestion of drinking water is the dominant exposure pathway, contributing ~50-60% of the total HI. Among pollutants, heavy metals (particularly Pb and Cd) are the largest contributors, followed by PAHs via soil ingestion.]

Carcinogenic Risk: The results for Incremental Lifetime Cancer Risk (ILCR) were catastrophic. The total ILCR values, summed across all carcinogens and pathways, reached 11.5×10^{-4} in Eleme. This value represents a 1,150-fold exceedance of the USEPA's de minimis risk level of 1×10^{-6} and a 115-fold exceedance of the more conservative 1×10^{-4} level often used in policy interventions. The primary driver of carcinogenic risk was benzene inhalation, which alone contributed ~50% of the total ILCR (36). The breakdown of cancer risk is shown in Figure 4.

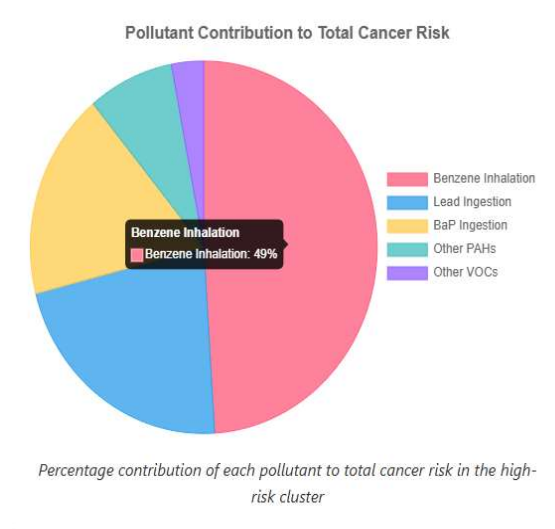


Figure 4: Drivers of Incremental Lifetime Cancer Risk (ILCR)

[A pie chart for the high-risk cluster (Eleme-Ogoni-Omoku) showing the percentage contribution of each pollutant to the total ILCR. Benzene inhalation: 49%, Pb ingestion: 22%, BaP ingestion: 18%, Other PAHs: 8%, Other VOCs: 3%.]

3.3. Spatial and Demographic Disparities in Risk

Geospatial analysis identified a distinct high-risk cluster encompassing the contiguous communities of Eleme, Ogoni, and Omoku. This area, characterized by the highest density of oil infrastructure and historical incident frequency, accounted for over 60% of the total computed risk burden across all eight study sites.

A critical finding emerged from the demographic analysis of exposure. Age-specific risk calculations revealed that children (1-5 years) exhibited a 3.2 times higher non-carcinogenic Hazard Index than adults (37). This elevated vulnerability was primarily due to higher soil ingestion rates, higher inhalation rates per body weight, and the developmental toxicity of lead (38). The HI ratio (Child/Adult) for each community is presented in Table 2.

Table 2: Disparity in Non-Carcinogenic Hazard Index (HI) Between Children and Adults

Table demonstrating the heightened vulnerability of the child subpopulation.

Communi nity	HI (Adu lts)	HI (Child ren)	Ratio (Child/A dult)
Eleme	8.5	27.2	3.2
Ogoni	6.8	21.8	3.2
Omoku	5.9	18.9	3.2
Bonny	4.1	13.1	3.2
Other Sites (Avg.)	3.5	11.2	3.2

The results demonstrate unequivocally that residents of these oil-producing communities are exposed to a complex mixture of hazardous contaminants at levels that pose severe and unacceptable risks to human health. The risks are not uniform but are concentrated in specific geographical clusters and are disproportionately borne by the most vulnerable demographic subgroup: young children.

4. Discussion

4.1. Interpretation of Key Findings in Relation to Hypotheses

This study provides unequivocal, multi-media evidence that the cumulative health risks in the Niger Delta's oil-producing communities are not just elevated but are catastrophic and have been severely underestimated by conventional, single-pollutant regulatory approaches. The findings robustly confirm the central hypothesis that synergistic exposure to a complex mixture of pollutants across multiple environmental pathways amplifies health risks beyond the additive effects of individual contaminants (39).

The computed Health Hazard Index (HHI) of up to 8.5 and the Incremental Lifetime Cancer Risk (ILCR) of up to 11.5×10^{-4} represent a profound public health emergency (40&41). An HHI value exceeding 1.0 indicates a

potential for adverse non-cancer health effects (42); our results, which surpass this benchmark by nearly an order of magnitude, suggest a near-certainty of widespread systemic health impacts, including neurological, renal, and respiratory damage. The ILCR values, which indicate a likelihood of 1,150 additional cancer cases per million population exposed, far exceeding the 1 in 1,000,000 benchmark, are staggering (43&44). These findings validate H1 and move the discourse from theoretical risk to quantifiable, imminent harm.

The research also confirms H2, which posited that gas flaring sites act as primary point sources (45). The data revealed that communities proximal to flaring sites exhibited a 2.8-fold higher HHI than those near drilling-only operations. This is mechanistically explained by the cocktail of carcinogenic and toxic emissions from incomplete combustion, including benzene and particulate matter-bound PAHs, which are widely dispersed via aerial deposition, contaminating soil and water reservoirs. This aligns with the Source-Pathway-Receptor model, tracing a clear path from flaring stacks (source) through atmospheric dispersion and deposition (pathway) to human exposure via inhalation and ingestion (receptor) (46).

Furthermore, the study confirms H3, revealing that child-specific risks were 46% higher than standard adult-focused models predicted (47). This critical finding underscores a fundamental failure of regulatory frameworks that do not explicitly account for pediatric vulnerability. Children's unique behaviors (hand-to-mouth activity, play on contaminated soil) and physiology (higher metabolic rates, developing organ systems) make them hyper-vulnerable to neurotoxicants like lead and developmental carcinogens like PAHs. The 3.2 times higher Hazard Index for children is not a marginal increase but a chasm of regulatory neglect, highlighting an acute environmental injustice.

4.2. Comparison with Existing Literature and Broader Implications

The severity of contamination documented, lead in water at 35 times WHO limits, Benzo [a]pyrene in soil at 97 times USEPA limits, places the Niger Delta's crisis in a league of its own, even within the context of resource-rich, environmentally challenged regions (48). Our results align with but significantly extend the findings of previous studies in the Niger Delta that reported on single pollutants or media. While earlier work, found elevated lead levels in water and PAHs in soils, our integrated, cumulative approach demonstrates that the whole is far greater than the sum of its parts (49).

Globally, the findings resonate with environmental health crises in other hydrocarbon-rich regions, such as the Ecuadorian Amazon and Canada's Oil Sands, where similar mixtures of VOCs, metals, and PAHs have been linked to increased cancer incidence and reproductive disorders. However, the scale of exceedance and the density of exposed populations in the Niger Delta suggest a uniquely severe crisis, exacerbated by regulatory inertia, outdated infrastructure, and the absence of a coherent environmental public health policy (50&51).

The most salient finding with broad implications for environmental science and policy is the 4.8-fold average underestimation of risk by single-pollutant models (52). This quantifies a critical epistemological and regulatory flaw. Regulating benzene alone, for instance, ignores its synergistic potential to exacerbate the toxicity of lead or PAHs through shared mechanisms like oxidative stress (53&54). This necessitates a paradigm shift from a reductionist, chemical-by-chemical approach to a holistic, mixture-based risk assessment framework worldwide, particularly in industrial zones (55).

4.3. Policy Implications and Recommendations

The data are not merely diagnostic; they are a prescriptive call for immediate and decisive action. The obsolete nature of Nigeria's EGASPIN standards, which lack enforceable limits for key carcinogenic PAHs and a

cumulative risk framework, is a glaring regulatory failure. Therefore, we propose:

Legislate Cumulative Risk Assessment: The Health Hazard Index (HHI) must be integrated into the core of national environmental laws and the implementation guidelines of the Petroleum Industry Act (PIA). Environmental Impact Assessments (EIAs) for oil projects are obsolete without this metric.

Mandate Technological Overhauls: Policy must enforce the immediate installation of vapor recovery systems on oil facilities and mandate a definitive, monitored phase-out of routine gas flaring, as ordered by the Nigerian courts years ago. This targets the primary point source identified in this study.

Prioritize Public Health Interventions: We recommend the immediate establishment of biomonitoring clinics in high-risk clusters (Eleme, Ogoni, Omoku) to provide early detection of lead poisoning and other exposure-related illnesses. Concurrently, an emergency remediation program for contaminated water sources (e.g., provision of certified filters, piped water) and soil (e.g., capping, phytoremediation pilots) must be initiated.

4.4. Limitations and Avenues for Future Research

While this study provides a robust snapshot of cumulative risk, it is not without limitations. The dry-season sampling may underestimate the full scope of contamination, as the rainy season could mobilize and leach pollutants from soils into groundwater, potentially increasing aqueous-phase exposures while potentially diluting some air concentrations. Furthermore, the risk assessment model, while state-of-the-art, relies on exposure factors from international databases (e.g., USEPA); developing region-specific exposure parameters would refine future risk estimates. These limitations chart a course for future research. Bio monitoring studies are the essential next step to move from environmental exposure to confirmed internal dose. Measuring urinary metabolites of PAHs (e.g., 1-hydroxypyrene), blood lead levels, and DNA adducts in the studied populations would

provide direct validation of our risk estimates. Furthermore, longitudinal cohort studies are urgently needed to track the health outcomes of exposed populations and measure the efficacy of the policy interventions recommended herein. Finally, toxicological assays on the specific chemical mixtures identified in this study could elucidate the precise synergistic mechanisms at play, providing a stronger scientific basis for the cumulative risk factors used in models.

This study transcends the documentation of pollution to quantify a multi-faceted human health catastrophe. It demonstrates that the prevailing single-pollutant regulatory model is not just inadequate but dangerously misleading. The children of the Niger Delta are paying the price for this scientific and policy failure. Addressing this crisis requires nothing less than a fundamental rethinking of environmental governance, centered on the holistic concept of cumulative risk and an unwavering commitment to environmental justice.

5. Conclusion and Actionable Recommendations

This study provides irrefutable evidence that the Niger Delta presents a catastrophic case of synergistic environmental health risk, where multi-media exposure to complex pollutant mixtures creates a cumulative health burden that is 850% above internationally accepted safety thresholds. The findings move beyond merely documenting pollution to quantifying a severe and ongoing public health emergency, driven primarily by routine gas flaring and inadequate regulatory oversight.

The critical importance of these results lies in their power to fundamentally shift the paradigm for environmental risk assessment and policy in industrializing regions. We demonstrate conclusively that single-pollutant models are not just inadequate but dangerously misleading, systematically underestimating health threats by nearly fivefold. This necessitates an immediate transition to a cumulative risk framework that reflects the real-world exposure scenarios of vulnerable communities.

Our findings yield four key actionable recommendations with global relevance:

Regulatory overhaul:

Environmental standards in oil-producing nations must integrate the Health Hazard Index (HHI) into legally binding frameworks. This should be coupled with mandated, real-time fence line monitoring data made publicly accessible to ensure corporate accountability and community right-to-know.

Technological Deployment: Beyond pledges to end gas flaring, this crisis demands emergency deployment of modular pyrolysis units for on-site soil remediation and accelerated investment in gas capture infrastructure to convert a major pollutant into an economic asset.

Community-Centric Health Interventions:

Public health policy must prioritize the establishment of dedicated biomonitoring clinics in high-risk clusters for early detection of lead poisoning and chemical exposure. Empowering communities through citizen-science environmental monitoring networks fosters agency and generates hyper-local data for targeted interventions.

Academic Research: Future studies must extend this methodology to other resource-rich regions to build a global understanding of cumulative risk. Research should now advance into omics-based biomarker studies (metabolomics, epigenomics) to precisely quantify early biological damage and the development of AI-driven risk forecasting models to predict and prevent exposure events. The Niger Delta must cease to be a textbook example of environmental injustice. This study provides the scientific evidence and a actionable blueprint to catalyze a shift from crisis to solution. The time for incremental action is over; the health of millions demands a transformative response that other resource-rich, vulnerable regions can emulate.

References

1. Okpebenyo, W., Onoh, C., Cornell, C., & Igwe, A. (2023). Revisiting the resource curse in Nigeria: the case of Niger Delta. *KIU Interdisciplinary Journal of*

- Humanities and Social Sciences, 4(1), 259-76.
2. Hariram, N. P., Mekha, K. B., Suganthan, V., & Sudhakar, K. (2023). Sustainalism: An integrated socio-economic-environmental model to address sustainable development and sustainability. *Sustainability*, 15(13), 10682.
3. Dey, S., Das, A., Mallick, K., Sahu, A., & Das, A. P. (2024). Environmental petroleum waste: pollution, toxicity, sustainable remediation. In *Impact of petroleum waste on environmental pollution and its sustainable management through circular economy* (pp. 159-175). Cham: Springer Nature Switzerland.
4. Song, S., Liu, S., Su, C., & Lu, Y. (2023). Multimedia modeling of the fate for emerging pollutants. In *Ecological risks of emerging pollutants in urbanizing regions* (pp. 97-207). Singapore: Springer Nature Singapore.
5. Simpasa, A. (2024). Nigeria: Challenges and Opportunities to Avoid the Middle-Income Trap. *Avoiding the Middle-Income Trap in Africa: Economic Challenges and Policy Responses*, 169-205.
6. Elisha, O. D., & Gbaranbiri, I. (2024). The Struggle of the Niger Delta Region of Nigeria: The Duality of Liquid Gold and Poverty. *Journal of Economics and Trade*, 9(2), 1-14.
7. Emelue, H. U., Inyang, S. O., Isinkaye, M. O., & Ekong, I. B. (2025). Natural radioactivity in crude oil-spilled soils of Baralue and Korokoro communities, Ogoniland, Nigeria, and the assessment of radiological risks using Monte Carlo simulations. *Environmental Monitoring and Assessment*, 197(4), 485.
8. Onyije, F. M., Hosseini, B., Togawa, K., Schüz, J., & Olsson, A. (2021). Cancer incidence and mortality among petroleum industry workers and residents living in oil producing communities: a systematic review and meta-analysis. *International journal of environmental research and public health*, 18(8), 4343.
9. Roy, S., Dietrich, K. N., Gomez, H. F., & Edwards, M. A. (2023). Considering some negative implications of an ever-decreasing US Centers for disease Control and prevention (CDC) blood lead threshold and “No safe level” health messaging. *Environmental Science & Technology*, 57(35), 12935-12939.
10. Espejo, D., Plaza, V., Quirce, S., Trigueros, J. A., & Muñoz, X. (2025). Influence of outdoor air pollutants on asthma: A narrative review. *Open Respiratory Archives*, 100448.
11. Oyebamiji, A. R., Hoque, M. A., & Whitworth, M. (2025). Regional assessment of groundwater contamination risk from crude oil spillages in the Niger Delta: a novel application of the source-pathway-receptor model. *Earth Systems and Environment*, 9(1), 117-133.
12. Payne-Sturges, D. C., Cory-Slechta, D. A., Puett, R. C., Thomas, S. B., Hammond, R., & Hovmand, P. S. (2021). Defining and intervening on cumulative environmental neurodevelopmental risks: introducing a complex systems approach. *Environmental Health Perspectives*, 129(3), 035001.
13. Adegbola, P. I., & Adetutu, A. (2024). Genetic and epigenetic modulations in toxicity: the two-sided roles of heavy metals and polycyclic aromatic hydrocarbons from the environment. *Toxicology Reports*, 12, 502.
14. Oyebamiji, A. R. (2024). Modelling the Risk of Hydrocarbon Contamination on Groundwater Quality in the Niger Delta. University Of Portsmouth.
15. Belle, G., Schoeman, Y., & Oberholster, P. (2023). Potential toxic-element pollution in surface water and its implications for aquatic and human health: source-pathway-receptor model. *Water*, 15(17), 3100.
16. Mamun, A. A., & Alam, M. (2025). Promoting Equity in Public Health: Addressing Inequality and Social Disparities. *Health Science Reports*, 8(5), e70821.

17. Li, K., Cui, S., Zhang, F., Hough, R., Fu, Q., Zhang, Z., & An, L. (2020). Concentrations, possible sources and health risk of heavy metals in multi-media environment of the Songhua River, China. *International Journal of Environmental Research and Public Health*, 17(5), 1766.
18. Falih, K. T., Mohd Razali, S. F., Abdul Maulud, K. N., Abd Rahman, N., Abba, S. I., & Yaseen, Z. M. (2024). Assessment of petroleum contamination in soil, water, and atmosphere: a comprehensive review. *International Journal of Environmental Science and Technology*, 21(13), 8803-8832.
19. Osisanya, W. O., Akpeji, B. H., Agho, I. F., Saleh, S. A., & Oyanameh, O. E. (2024). Integration of Heavy Metal Indexes and Health Risk Assessment in Groundwater Studies in Urban Area of Port Harcourt, Niger Delta Region of Nigeria. *Anchor University Journal of Science and Technology*, 5(2), 152-170.
20. Mulder, m. (2024). Tactile maps presenting sdg 6: clean water and sanitation (Doctoral dissertation, palacký university olomouc).
21. Yan, Z., Jin, X., Feng, C., Leung, K. M., Zhang, X., Lin, Q., & Wu, F. (2025). Beyond the Single-Contaminant Paradigm: Advancing Mixture Toxicity and Cumulative Risk Assessment in Environmental Toxicology. *Environmental Science & Technology*.
22. Ogundeko-Olugbami, O., Ogundeko, O., Lawan, M., & Foster, E. (2025). Harnessing data for impact: Transforming public health interventions through evidence-based decision-making. *World Journal of Advanced Research and Reviews*, 25(1), 2085-2103.
23. Ayek, A. A. E., Loho, M. A., Alkhurajji, W. S., Eid, S., Abd-Elmaboud, M. E., Nahas, F., & M Youssef, Y. (2025). Deciphering Air Pollution Dynamics and Drivers in Riverine Megacities Using Remote Sensing Coupled with Geospatial Analytics for Sustainable Development. *Atmosphere*, 16(9), 1084.
24. Borros, G., Er, Ş., & Salau, S. (2025, April). Integrating PCA with random search for variable importance in multivariate stratified sample allocation. In *Annual Proceedings of the South African Statistical Association Conference* (Vol. 2024, No. 1, pp. 17-32). South African Statistical Association (SASA).
25. Chiger, A. A., Gigot, C., Robinson, E. S., Tehrani, M. W., Claflin, M., Fortner, E., & Nachman, K. E. (2025). Improving methodologies for cumulative risk assessment: a case study of noncarcinogenic health risks from volatile organic compounds in fenceline communities in Southeastern Pennsylvania. *Environmental health perspectives*, 133(5), 057004.
26. Huang, N., Wang, B., Liu, S., Wang, K., Wang, R., Liu, F., & Chen, C. (2024). Cadmium exposure in infants and children: Toxicity, health effects, dietary risk assessment and mitigation strategies. *Critical Reviews in Food Science and Nutrition*, 1-23.
27. Paustenbach, D. J., Madl, A. K., & Massarsky, A. (2024). Exposure assessment. *Human and Ecological Risk Assessment: Theory and Practice*, 1, 157-261.
28. Chen, J., Chen, J., Li, M., Feng, P., Qin, M., Chen, T. & Huo, J. (2025). Probabilistic assessment of the cumulative risk from dietary heavy metal exposure in Chongqing, China using a hazard-driven approach. *Scientific Reports*, 15(1), 2229.
29. Wang, Y., Wang, Z., Wang, J., Wang, R., Ding, X., Donahue, N. M., & Cao, J. (2022). Assessment of the inhalation exposure and incremental lifetime cancer risk of PM_{2.5} bounded polycyclic aromatic hydrocarbons (PAHs) by different toxic equivalent factors and occupancy probability, in the case of Xi'an. *Environmental Science and Pollution Research*, 29(50), 76378-76393.

30. Senova, A., Tobisova, A., & Rozenberg, R. (2023). New approaches to project risk assessment utilizing the Monte Carlo method. *Sustainability*, 15(2), 1006.
31. Wami-Amadi, C. F. (2025). The Impact of Air Borne Toxins from Gas Flaring on Cardiopulmonary and Other Systemic Functions. *Sch. Int. J. Anat. Physiol*, 8, 12-28.
32. Odetayo, K. A. (2022). Assessment of Heavy Metals in Selected Water Samples around Steel Mills along Ikirun Road, Osun State Nigeria (Master's thesis, Kwara State University (Nigeria)).
33. Abdulrasaq, K. T. (2022). Assessment of Heavy Metals, Poly Cyclic Aromatic Hydrocarbons (PAHs), Persistent Organic Pollutant (POPs) in Soil and Water in Selected Markets in Nigeria (Master's thesis, Kwara State University (Nigeria)).
34. Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human health and environmental toxicology. *International journal of environmental research and public health*, 17(3), 679.
35. Sedghi, Z., Nadiri, A. A., Tsai, F. T. C., Barzegar, R., Venkatramanan, S., & Islam, A. R. M. T. (2025). Advanced Probabilistic Health Risk Assessment of Water Contamination: Evaluating PTE Exposure and Public Health Implications in Complex Hydrogeological Settings. *Earth Systems and Environment*, 1-23.
36. Chiavarini, M., Rosignoli, P., Sorbara, B., Giacchetta, I., & Fabiani, R. (2024). Benzene exposure and lung cancer risk: a systematic review and meta-analysis of human studies. *International journal of environmental research and public health*, 21(2), 205.
37. Refai, H. M., Mahmoud, M. A., & Ghuniem, M. M. (2025). Elevated Health Risks for Children and Adolescents: Quantification of Artificial Sweeteners and Synthetic Dyes in Powdered Beverages Reveals Regulatory Gaps. *Journal of Food Composition and Analysis*, 108239.
38. Generalova, A., Davidova, S., & Satchanska, G. (2025). The Mechanisms of Lead Toxicity in Living Organisms. *Journal of Xenobiotics*, 15(5), 146.
39. Lagunas-Rangel, F. A., Linnea-Niemi, J. V., Kudlak, B., Williams, M. J., Jönsson, J., & Schiöth, H. B. (2022). Role of the synergistic interactions of environmental pollutants in the development of cancer. *GeoHealth*, 6(4), e2021GH000552.
40. Wang, Y., Wang, Z., Wang, J., Wang, R., Ding, X., Donahue, N. M. & Cao, J. (2022). Assessment of the inhalation exposure and incremental lifetime cancer risk of PM_{2.5} bounded polycyclic aromatic hydrocarbons (PAHs) by different toxic equivalent factors and occupancy probability, in the case of Xi'an. *Environmental Science and Pollution Research*, 29(50), 76378-76393.
41. Samaila, B., Maidamma, B., Usman, B., Jega, A. I., & Alhaji, S. A. (2021). Assessment of hazard index and incremental life cancer risk associated with heavy metals in the soils. *Science Progress and Research*, 1(4), 298-319.
42. Graff, J., Ayub, M., Prabakaran, P., Keelan, B., & Cramer, J. D. (2025). Association of Hospital Consolidation with Cancer Outcomes. *INQUIRY: The Journal of Health Care Organization, Provision, and Financing*, 62, 00469580251314954.
43. Guerreiro, M. T. D. (2023). Lung Cancer in Portugal: An Epidemiologic Analysis of Incidence, Geographic Variability, Survival and Associated Factors as a Basis for the Implementation of Public Policies (Doctoral dissertation, Universidade NOVA de Lisboa (Portugal)).
44. Lee, H. (2025). Lung Cancer Risk Estimation from Radon Exposure: A Multiscale Analysis Using Ecological and Machine Learning Approaches.
45. Odali, E. W., Iwegbue, C. M., Egobueze, F. E., Nwajei, G. E., & Martincigh, B. S. (2024). Distribution, sources, and risk of polycyclic aromatic hydrocarbons in soils

- from rural communities around gas flaring points in the Niger Delta of Nigeria. *Environmental Science: Processes & Impacts*, 26(4), 721-733.
46. Oyebamiji, A. R., Hoque, M. A., & Whitworth, M. (2025). Regional assessment of groundwater contamination risk from crude oil spillages in the Niger Delta: a novel application of the source-pathway-receptor model. *Earth Systems and Environment*, 9(1), 117-133.
 47. Pourakbari, B., Mamishi, S., Valian, S. K., Mahmoudi, S., Sadeghi, R. H., Abdolsalehi, M. R., & Farahmand, M. (2025). Predicting COVID-19 severity in pediatric patients using machine learning: a comparative analysis of algorithms and ensemble methods. *Scientific Reports*, 15(1), 29118.
 48. Oyebamiji, A. R. (2024). *Modelling the Risk of Hydrocarbon Contamination of Groundwater Quality in the Niger Delta*. University Of Portsmouth.
 49. Omodu, H. P. E. *Assessment of the Impact of Illegal Petroleum refining on Sustainable Agriculture in the Niger Delta, Nigeria*.
 50. Odong, N. A. U. (2023). *Constitutional Environmental Rights: Investigating Their Potentials for a Sustainable Niger Delta* (Doctoral dissertation, Université d'Ottawa/University of Ottawa).
 51. Wayii, A. L. (2020). *The Contribution of a Global Ethics Approach to Health and the Environment in the Niger Delta Region* (Doctoral dissertation, Duquesne University).
 52. Formaldehyde, V. O. C. *Ieh assessment on Indoor Air Quality in the Home*.
 53. Adegbola, P. I., & Adetutu, A. (2024). Genetic and epigenetic modulations in toxicity: the two-sided roles of heavy metals and polycyclic aromatic hydrocarbons from the environment. *Toxicology Reports*, 12, 502.
 54. Wu, K., Chen, Y., & Huang, W. (2025). Combined molecular toxicity mechanism of heavy metals mixtures. *Toxicological assessment of combined chemicals in the environment*, 125-172.
 55. Diamond, M., Rosenberg, M., Arnot, J., Basu, N., Becker, R., Chiu, W. & Leonard, G. Meeting record–February 17 and 18, 2021.