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Assessment of Environmental and Occupational Hazards Associated with Crude Oil Exploitation: A Toxicokinetic and Engineering-Based Framework for Sustainable Mitigation

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Abstract

The study evaluated environmental and occupational risks, associated with crude oil exploitation in Niger delta in Nigeria, using an integrative toxicokinetic-engineering framework. Environmental samplings of air, water, land, and sediment were conducted in Nembe, Gbaramatu, and Bonny, and analysed using GC-MS and AAS for quantitative purposes. While PK-Sim, under the benefit of PBPK modelling, provided an estimation of the kinetics of benzene and benzo[a]pyrene. Benzoic acid-deriving compounds urinary benzoic acid levels in 72.6% of workers exceeded the

benzene BEIs (t,t-muconic acid: 615.2 ug/g), blood lead levels of 83.4% were above 10ug/dl (mean=17.3ug/dl), and 69.8% had PAN-DNA adducts more than 4ng/mL. Logistic regression analysis revealed that exposure to gas flaring (OR = 3.42, $p < 0.001$) and more than 10 years of service (OR = 3.12, $p = 0.002$) were significant predictors of benzene burden. Good relationships were documented between pollutants and biomarkers (for example, benzene, t-MA: $r = 0.681$, $p < 0.001$). PCA explained 90.5% of the variance using three axes of exposure, which comprised VOCs, heavy metals, and PAHs. Risk Quotients were at high risk levels: benzene (RQ = 3.00), lead (RQ = 3.75), and arsenic (RQ = 3.00). The engineering audit identified critical failures: a pipeline break (RPN = 250), gas detector problems (RPN = 216), and non-implementation of SCADA. The study advances the science of exposures by confirming biomonitoring-toxicokinetic relations and proposing the application of predictive maintenance, biomarker monitoring, the policy of Personal Protective Equipment, and specific pollutant remediation as a way to decrease total toxic exposure.

Keywords: Toxicokinetics, Occupational Exposure, PBPK Modeling, Crude Oil Exploitation, Environmental Sampling, Biomonitoring

Introduction

Oil exploitation remains a significant source of energy worldwide and a key contributor to national income generation in developing nations, such as Nigeria, where oil fields are abundant. Nevertheless, the processes of extraction, refinement, and transportation have been irreversibly linked to fraught environmental degradation and employment hazards (Nduka & Orisakwe, 2011; Isangadighi & Udeh, 2023). In the Niger Delta region, which accounts for most of Nigeria's oil production, continuous oil spills, gas flaring, and pipeline leaks have occurred, resulting in soil and groundwater contamination, ecological imbalance, and public health emergencies (Bodo & Gimah, 2020; Anejionu et al., 2015). Of equal interest are the occupational hazards that workers in crude oil facilities face, as they often encounter hazardous chemicals such as volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), hydrogen sulfide, and heavy metals (including lead and cadmium), among others. There are numerous acute and chronic effects that the substances are known to be associated with (respiratory diseases, neurotoxicity, genotoxicity, carcinogenesis) (Moses et al., 2025; Ekpenyong & Asuquo, 2017; Ite & Ibok, 2013; Ikhide, 2025). Despite the severity of such exposures, adequate systems of occupational health surveillance are

lacking in many oil-producing environments, and engineering controls are inadequately enforced, often being technologically unsophisticated (Isangadighi & Udeh, 2023). Existing mitigation measures are still in place across the board. Environmental risk assessments typically do not include a detailed evaluation of toxicokinetics, and engineering strategies often differ from exposure modelling information. It is toxicokinetics (the system of absorption, distribution, metabolism, and excretion (ADME) of toxicants) that is necessary to predict the internal dose and develop biological exposure indices, as well as to inform the development of timely interventions (Isangadighi & Ukudo, 2025). However, its use in the oil industry for risk management is minimal, particularly in African contexts.

Similarly, a variety of engineering control faults, such as the low integrity of pipelines or the lack of automated shutdown systems, have been frequently reported in the Nigerian petroleum industry (Eregha & Irughe, 2009; Islam, 2021). These technical breakdowns only increase the risks of environmental and human exposure and also undermine the overall goals of sustainable resource management and worker protection. It is against this background that this study aims to conduct a detailed evaluation of the environmental and occupational risks associated with crude oil exploitation by applying a combined toxicokinetic and engineering-based approach. This study can be used to develop a contextually and scientifically reasonable approach to the sustainable control of hazards by simulating the adsorption behaviour of the most significant types of toxic substances and assessing the efficiency of various engineering control measures. The overall expectation is to promote interdisciplinary knowledge; enhance exposure monitoring, communicate policy change, and improve environmental quality as well as occupational health in the communities that produce oil.

Environmental Hazards Associated with Crude Oil Exploitation

The exploration of crude oil presents a multifaceted and multilateral set of environmental risks, primarily manifesting as ecosystem destruction, soil pollution, air pollution, and groundwater pollution. The Niger Delta, in particular, has been branded as one of the most petroleum-polluted places in the world wherein thousands of oil spills, as well as a regular gas-flaring process, not only modified the ecological zoning but also made the majority of territories unusable as agricultural and fish-catching lands (Anejionu et al., 2015). The transfer of hydrocarbons and heavy metals, including lead, cadmium, arsenic, and vanadium, to terrestrial and aquatic ecosystems disturbs ecological balances and causes bioaccumulation in plant and animal bodies, with subsequent effects on human food safety (Ite & Ibok, 2013). Pollution flaring has also been closely linked to respiratory morbidity in communities adjacent to production fields, including sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (Isangadighi & Ukudo, 2025). In addition to this, oil-based activities have released deadly persistent organic

pollutants (POPs) and polycyclic aromatic hydrocarbons (PAHs) into sediments and water bodies, many of which are carcinogenic and mutagenic (Osuji & Adesiyan, 2005). Such contaminants remain in the environment long after they have been released, and their long-term individual impacts are often understated in standard environmental impact analyses.

Occupational Health Risks in Crude Oil Production

Oil and gas workers work in a situation that is full of chemical, physical, biological, and ergonomic risks. Chronic exposure to VOCs, such as benzene, toluene, and xylene, may lead to hematotoxicity, central nervous system disease, and even leukaemia in extreme exposure cases (Ekpenyong & Asuquo, 2017). Additionally, oilfield employees are exposed to heat, noise, ultraviolet radiation, and vibration, which can lead to long-term health consequences, including hearing loss, heatstroke, and musculoskeletal injuries (Ike et al., 2020). Most oilfield activities in developing nations do not meet standards, despite the availability of regulatory parameters, such as the occupational health guidelines of the ILO and the permissible exposure limits (PELs) of OSHA. Factors such as inadequate training, a lack of proper personal protective equipment (PPE) culture, and irregular safety audits also contribute to these risks (Isangadighi & Udeh, 2023). According to empirical studies, the frequent reports submitted by addicted Nigerian oil workers include chronic fatigue, dizziness, respiratory issues, and dermal irritation, most often during upstream and offshore work (Ikhide, 2025).

Toxicokinetics of Petroleum-Derived Toxicants

Toxicokinetics, which encompass components of absorption, distribution, metabolism, and excretion (ADME), are crucial in understanding the behaviour of petroleum-based toxicants in a biological system. As an example of benzene, this compound can be easily absorbed through the inhalation pathway and the skin, stored in fatty tissues, and processed into toxic intermediates by the liver, such as benzene oxide. It is later excreted in urine as phenol and trans, trans-muconic acid (Airede & Asibor, 2025). The biomarkers provide a measure of internal dose indicators and can be used in the surveillance of exposure among oil workers. A biotransformation enzymatic pathway acts upon the PAHs through the process of cytochrome P450, enabling the formation of DNA adducts and serving as initiators of cancer (Konstantinova et al., 2021; Isangadighi et al., 2025). These compounds have a wide range of half-lives and residence times, which are based on their molecular weight and the efficiency of metabolic detoxification processes. Therefore, a toxicokinetic method can enhance the accuracy of health risk assessment by leveraging the correlation between environmental levels and biological effect thresholds (Sweeney et al., 2015).

Engineering Control Systems in Oil Operations

Proper engineering controls provide a crucial safeguard in reducing occupational and environmental risks associated with petroleum activities. They are structural containment systems, pipeline pressure control devices, automatic shutdown systems, corrosion monitoring sensors and gas detection alarms. Regrettably, in most oilfields in sub-Saharan Africa, such systems are either not functioning or have been neglected (Eregha & Irughe, 2009). The absence of a predictive maintenance program and live data analytics also increases the likelihood of a system malfunction triggering a disastrous spill or fire. On a global scale, Hazard and Operability (HAZOP) studies and Failure Mode and Effects Analysis (FMEA) have been recommended as proactive engineering tools for identifying and planning risks (Islam et al., 2025; Khakzad et al., 2013). Nevertheless, systems engineering efforts are limited, and the lack of enforcement of regulations often leads to a poor uptake of such activities within Nigerian installations. The result is an inherited inability to predict and mitigate risks, which increases the likelihood of workplace accidents and environmental pollution.

Integrative Frameworks for Sustainable Hazard Mitigation

Several integrative frameworks have emerged to bridge the gap between environmental monitoring and occupational risk assessment. They are the human health risk assessment framework of the U.S. Environmental Protection Agency (EPA), the WHO IPCS risk assessment toolkit and occupational safety systems based on ISO 45001. However, these models seldom involve the use of toxicokinetic parameters and even fail to provide site-specific engineering controls (van Leeuwen & Vermeire, 2007). An integrative strategy that combines a toxicokinetic model with engineering diagnostics offers a promising solution. With this kind of framework, hazardous exposures can be identified early enough to identify vulnerable subsystems and design specific mitigation strategies. It aligns with Sustainable Development Goals (SDGs) 3 (Good Health and Well-being), 9 (Industry, Innovation, and Infrastructure), and 12 (Responsible Consumption and Production), presenting an opportunity to achieve sustainable work in the oil industry.

METHODOLOGY

The research employed an interdisciplinary, mixed-methodological approach that enabled a comprehensive evaluation of environmental hazards and occupational exposure associated with crude oil exploitation. The study was conducted in some of the petroleum-producing locations in Niger Delta of Nigeria such as Nembe in the Bayelsa State of Nigeria, Gbaramatu in the Delta State of Nigeria and Bonny in River State of Nigeria. The identified sites here were chosen due to their current upstream oil-related activities as well as previous environmental pollution and work-related exposure. To determine the levels of petroleum-derived contaminants in the ambient air, surface water, groundwater, soil,

and sediment, environmental sampling was conducted. Analysis of samples was performed using portable real-time air quality monitors, Gas Chromatography Mass spectrometry (GC-MS) and Atomic Absorption Spectrophotometry (AAS) to determine the presence of volatile organic compounds (VOCs) such as benzene and toluene, polycyclic aromatic hydrocarbons (PAHs) such as naphthalene and benzo[a]pyrene and heavy metals, including lead, cadmium, arsenic and chromium. These samples were collected during both wet and dry seasons to assess the changes in pollutant distribution over time. To benchmark observed concentrations, standards from the World Health Organisation (WHO), the Nigerian National Environmental Standards and Regulations Enforcement Agency (NESREA), and the United States Environmental Protection Agency (USEPA) were used. At the same time, a systematic occupational exposure study was undertaken, including the use of structured questionnaires, personal air measurements, walk-throughs during the work shift, and hazard identification (HAZID). One hundred and fifty rig operators, maintenance technicians, and field engineers were surveyed to record the use of PPE pattern, period of exposure, physical symptoms and the perception of risks.

To address this concurrently, toxicokinetic modelling is used to predict the biological behaviour of common toxicants in exposed employees. The toxicokinetic aspect focused on the absorption, distribution, metabolism, and excretion (ADME) of benzene and benzo[a]pyrene through a physiologically based pharmacokinetic (PBPK) model. The quantum chemical modeling of the molecular interactivity based on BIOVIA Materials Studio was applicated, whereas the simulation of the toxicant kinetics based on the inputs of the body weight, the exposure duration, the inhalation rates, the tissue partition coefficients, the metabolic clearance rates, and the environment concentration level extracted due to field sampling was implemented in a PK-Sim(r). Urine and blood samples were assessed in terms of biomonitoring data, including urinalysis (to determine phenol, hippuric acid, and trans, trans-muconic acid as biomarkers of the body's exposure to benzene and toluene) and blood tests (to measure lead, cadmium, and PAH-DNA adducts). These biological indices helped validate the results provided by the PBPK model, estimate internal doses, and generate plasma concentration-time curves. Through this type of modelling, the residence time of toxicants, maximum plasma levels, and the levels at which the toxic effects become significantly likely could be approximated. Exposure-internal biomarker data and environmental concentrations were combined to enhance the exposure-response relationship and better quantify the exposure-related occupational health risk.

Besides the toxicological assessment, audits of the engineering systems were performed, giving an opportunity to determine infrastructural flaws and to evaluate the effectiveness of the implemented control systems. An engineering safety checklist was used based on the OSHA Process Safety Management (PSM) and the American Petroleum Institute (API

RP 752) to conduct a technical tour of oilfield installations. An evaluation of the integrity, operational reliability, and containment of critical infrastructures, including storage tanks, gas separators, compressors, pipeline networks, and flare stacks, was conducted. An FMEA (Failure Mode and Effects Analysis) was then conducted to identify all possible modes of failure in this engineering system. They were assessed and rated based on severity (S), the plausibility of their occurrence (O), and detectability (D), out of which the Risk Priority Number (RPN = S x O x D) was calculated to prioritise areas of intervention. The Hazard and Operability (HAZOP) study, conducted in collaboration with site engineers, aimed to simulate potential deviations in the process (for example, flow reversal, pressure buildup, thermal instability) and provide specific measures that could be implemented to correct these issues. The information about these engineering assessments was combined with toxicokinetic data to develop a mitigation strategy. When processing environmental, biological, and engineering data, SPSS (version 26) and MATLAB were used to perform statistical analysis. Exposure-outcome relations were identified by descriptive statistics, multivariate regression, and correlation matrices, whereas a PK-Sim was applied to visualise toxicokinetic simulations. The study received ethical clearance through a university-based institutional review board, and all participants provided their informed consent. The study was strictly confidential, and all the field activities were carried out to the internationally recognised standards of environmental health and occupational safety.

RESULTS

Table 1: Mean Concentration of Selected Pollutants in Environmental Samples (Dry and Wet Seasons)

Pollutant	Medium	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)	WHO/NESREA Limit
Benzene (µg/m³)	Ambient Air	124.3 ± 15.8	87.6 ± 12.4	50
Toluene (µg/m³)	Ambient Air	210.9 ± 24.5	165.4 ± 17.2	200
Benzo[a]pyrene (µg/kg)	Soil	5.81 ± 0.72	4.26 ± 0.55	1
Lead (Pb) (mg/L)	Groundwater	0.092 ± 0.013	0.076 ± 0.009	0.01
Cadmium (mg/kg)	Sediment	2.64 ± 0.41	1.89 ± 0.28	0.5
pH	Surface Water	5.3 ± 0.4	5.9 ± 0.3	6.5–8.5

Table 2: Summary of Occupational Exposure Patterns and Reported Symptoms Among Oilfield Workers

Exposure Parameter	Frequency (%)
Use of PPE (consistently)	41.3%
Worked >10 hours/day	62.7%
Exposure to gas flaring zones	79.3%
Reported symptoms:	
Headache	66.7%
Eye/skin irritation	59.3%
Shortness of breath	45.3%
Persistent fatigue	38.0%
Dizziness	40.7%
Access to safety induction/training	48.7%
Accident or near-miss in past 6 months	27.3%

Table 3: Biomarker Levels in Biological Samples of Exposed Workers

Biomarker	Biological Matrix	Mean ± SD	Biological Exposure Index (BEI)	% Exceeding BEI
Trans,trans-muconic acid (µg/g)	Urine	615.2 ± 89.3	500	72.6%
Phenol (µg/mL)	Urine	18.4 ± 3.2	16	65.1%
Hippuric acid (µg/mL)	Urine	2.15 ± 0.47	1.60	58.0%
Blood Lead Level (µg/dL)	Blood	17.3 ± 3.6	10	83.4%
PAH-DNA Adducts (ng/mL)	Blood	7.82 ± 1.05	4.0	69.8%

Table 4: PBPK Model Simulated Results for Benzene and Benzo[a]pyrene

Compound	Parameter	Value (Mean)	Interpretation
Benzene	Peak Plasma Conc. (Cmax)	9.4 µg/mL	Indicates high systemic absorption
	Time to Peak (Tmax)	1.5 hours	Rapid onset post-exposure
	Elimination Half-life (t½)	10.3 hours	Prolonged systemic retention
Benzo[a]pyrene	Peak Plasma Conc. (Cmax)	3.1 µg/mL	Lower but more persistent in tissue
	Time to Peak (Tmax)	4.2 hours	Delayed systemic distribution
	Estimated DNA Adduct Formation Rate	0.78 ng/mL/hr	High carcinogenic potential

Table 5: FMEA Results for Selected Engineering Systems

Component	Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	RPN (S × O × D)	Risk Level
Gas detector	Sensor failure	9	6	4	216	Critical
Flare stack	Delayed ignition	8	5	5	200	High
Storage tank valve	Corrosion-induced leakage	7	6	4	168	High
Compressor unit	Overheating	6	4	3	72	Medium
Pipeline system	Rupture under pressure	10	5	5	250	Critical

Table 6: Logistic Regression – Predictors of High Urinary t,t-Muconic Acid Levels (Above BEI)

Variable	B (Coeff.)	SE	OR (95% CI)	p-value
Exposure > 10 years	1.14	0.39	3.12 (1.52–6.42)	0.002
Consistent PPE usage (No)	0.89	0.32	2.44 (1.30–4.57)	0.006
Work in gas flaring area	1.23	0.36	3.42 (1.67–7.00)	<0.001
Age > 45 years	0.44	0.30	1.55 (0.86–2.81)	0.137

Table 7: Pearson Correlation Between Environmental Pollutants and Biomarker Levels

Environmental Pollutant	Biomarker	Correlation Coefficient (r)	p-value
Ambient Benzene (µg/m³)	t,t-Muconic Acid (µg/g)	0.681	<0.001
Air Toluene (µg/m³)	Hippuric Acid (µg/mL)	0.604	<0.001
Soil Benzo[a]pyrene	PAH-DNA Adducts (ng/mL)	0.532	0.001
Groundwater Lead (mg/L)	Blood Lead Level (µg/dL)	0.701	<0.001

Table 8: Site-Based Comparison of Key Environmental and Biomarker Values

Parameter	Nembe	Gbaramatu	Bonny	p-value (ANOVA)
Air Benzene (µg/m³)	132.6	118.3	106.1	0.018
Urinary t,t-MA (µg/g)	645.8	598.4	588.1	0.041
Groundwater Lead (mg/L)	0.096	0.085	0.078	0.026

Interpretation: Nembe shows significantly higher pollutant levels and biomarker accumulation.

Table 9: Engineering Control Status and Effectiveness Ratings (by Site)

Control Measure	Nembe	Gbaramatu	Bonny	Status	Effectiveness (%)
Gas Detection Sensors	Partial	None	Functional	Moderate to Poor	52%
Pressure Relief Valves (PRV)	Present	Obsolete	Present	Fair to Critical	64%
SCADA Monitoring	Nonexistent	Partial	Functional	Poor to Moderate	45%
Flare Stack Ignition System	Manual	Faulty	Automated	Poor to Good	59%

Bonny outperforms others in engineering control performance, while Gbaramatu lags behind.

Table 10: PCA Component Loadings After Varimax Rotation

Pollutant	PC1 (Organic VOCs)	PC2 (Heavy Metals)	PC3 (High-MW PAHs)
Benzene	0.897	0.221	0.140
Toluene	0.872	0.136	0.104
Naphthalene	0.731	0.204	0.491
Lead (Pb)	0.124	0.925	0.210
Cadmium (Cd)	0.215	0.889	0.150
Arsenic (As)	0.238	0.842	0.231
Benzo[a]pyrene	0.321	0.290	0.866

Eigenvalues and Explained Variance

Component	Eigenvalue	% Variance Explained	Cumulative %
PC1	3.14	44.9%	44.9%
PC2	2.05	29.3%	74.2%
PC3	1.14	16.3%	90.5%

PC1 clusters VOCs, primarily benzene and toluene, indicating an inhalation risk axis; PC2 groups heavy metals, reflecting a chronic toxicity/metal contamination axis and PC3 isolates high-molecular-weight PAHs, indicating potential carcinogenicity via ingestion or dermal absorption.

Table 11: Risk Quotients for Selected Pollutants

Pollutant	Exposure Pathway	Chronic Daily Exposure (mg/kg/day)	RfD (mg/kg/day)	RQ	Risk Level
Benzene	Inhalation	0.012	0.004	3.00	High Risk
Lead (Pb)	Drinking water	0.0015	0.0004	3.75	High Risk
Cadmium	Water ingestion	0.0007	0.001	0.70	Moderate Risk
Benzo[a]pyrene	Soil ingestion	0.00013	0.0003	0.43	Low Risk
Toluene	Inhalation	0.014	0.08	0.18	Negligible Risk
Arsenic	Water ingestion	0.0009	0.0003	3.00	High Risk

RQ > 1 indicates potential for adverse non-carcinogenic health effects.

DISCUSSION

Environmental Contamination and Seasonality

The resultant ambient benzene concentrations in our measurements, 124.3±15.8 µg/m 3 (dry) and 87.6±12.4 µg/m^3 (wet) (Table 1), do not merely exceed standards; they are simply out of this world. Conversely, a study conducted by Okoh et al. (2014) in Ogoniland in 2014 revealed that the level of benzene was even higher than the dangerously high levels of 25.7, 23.2, and 2. The study recorded 45 times higher values in its measurements, which is undoubtedly an indication of environmental collapse. The results are similar to those reported by Gisbert et al. (2018), who found that benzene levels in flaring activities in the Niger Delta repeatedly exceeded 80µg/m³ during the dry seasons, based on data obtained in 2018, which is comparable to our findings. In the same way, our value of 5.81±0.72ug/kg for soil benzo[a]pyrene (Table 1) surpasses the one ug/kg cutoff and compares to Udom et al. (2019) estimating average BaP in floodplain soils of oil infrastructures at 6.3ug/kg. The values indicate long-term contamination, which is compatible with long-term exposure to crude oil. Our result was also confirmed by a study by Fortson et al. (2020), which found BaP consistently exceeding the limit at a site with a significant oil spill. Lead in the groundwater is also concerning (0.092±0.013 mg/L, which is nearly 9 times the maximum permissible level of 0.01mg/L). This result is similar to that of Mishra et al. (2021), which reported a mean water lead concentration of 0.073. These values are slightly above, indicating evidence of contemporary or recent contamination rather than industrial heritage. All these data reiterate that the region continues to fail safe environmental standards.

Occupational Exposure and Worker Health: Patterns, Predictors, and Physiological Consequences

The occupational setting in crude oil-producing regions, as discussed in this paper, is a field of toxicological battle. In this region, workers are systematically exposed to hazardous elements without proper safeguards, inadequate policy implementation, and ineffective environmental control mechanisms. According to the data on Table 2, just 41.3% of the oilfield employees always wear the personal protective equipment (PPE), 62.7% have to work more than 10 hours every day, and the most terrible statistic 79.3% of the oilfield line is situated in the area very close to the active gas-flaring locations. These circumstances constitute a contravention not only of international occupational safety norms (for example, OSHA 1910, ILO C155) but also of the most fundamental requirements of environmental justice. Such risk factors of the behavioural type are not special or anecdotal; they are merely converted into clinical symptomatology and measurable health outcomes. Six (6) out of every ten (10) workers who participated in the survey reported cases of headache (66.7%), respiratory distress (45.3%), and dizziness-fatigue (40.7%). These are standard symptoms of contact with highly volatile materials

(VCMs) like benzene, toluene, and xylene, which are famously known to affect the central nervous system, cause respiratory irritation, and induce blood toxicity at low concentrations. Ekpenyong and Asuquo's (2017) study recorded the same characteristics of symptom cluster among petroleum logistics of Rivers State, corroborating the fact that the clinical manifestations are persistent and consistent across the oil-producing regions of Nigeria.

To identify statistically significant predictors of high internal benzene biomarkers (urinary t,t-MA levels), logistic regression analysis was employed (see Table 6). The findings were convincing and supported by strong scientific evidence. The odds of workers with more than 10 years of cumulative exposure exceeding the benzene biological exposure indices (BEIs) were 3.12 times more likely (OR = 3.12, $p = 0.002$). The odds of non-users having elevated biomarkers were 2.44 times higher ($p = 0.006$) compared to users. The most significant risk factor was identified among those posted near flaring zones, with an odds ratio of 3.42 ($p < 0.001$). The results provide powerful causal relationships between workplace exposures and internal exposure to toxicants. They also correlate well with the study conducted by Ite and Ibok (2013), who found that proximity to gas flaring increased the incidence of haematological risk from benzene by 2.8 times in oil workers in Cross River State. The factor of shift duration turned out to be a decisive confounding variable. Employees who work 10-hour shifts and longer are not only increasing their daily and cumulative exposure to inhalation and dermal contact, but also compromising the metabolic clearance window of toxicants like benzene, whose plasma half-life is approximately 1012 hours, as indicated by our findings in Table 4. There is a toxicological effect of this exposure and retention time overlap, the end result of which leads to bioaccumulation and chronic organ loading, but especially to the liver, bone marrow and renal systems. It is worth mentioning that no national law in Nigeria has so far restricted the duration of shifts for oilfield employees, as opposed to international best practices as listed by the International Association of Oil & Gas Producers (IOGP) (Checchi, 2020).

Policy-wise, these findings speak for themselves. The low rate of compliance with PPE use (41.3%) is not due to indifference and a lack of knowledge among workers, as more than 75% of the workers surveyed are already aware of the danger. Still, it is the systematic neglect, impotence of the regulatory apparatus, and the inefficiency of the occupational health profile in most plants and enterprises. This can be attributed to the fact that the UNEP (2011) Environmental Assessment of Ogoniland revealed that more than 80% of all surveyed oil installations lack trained safety officers or have not established formal exposure monitoring procedures. Comparatively, Algeria and Egypt petroleum sites had measures above 85% compatible with PPE because legislation was imposed and government auditors were sent (WHO, 2015). Moreover, the occupational health results in this paper are more severe compared to those obtained by Mmom and Iluyemi (2018) in Port Harcourt, where only 53.2% of the oil logistics workers reported complaints about

chronic headaches, and 35.6% complained about breathing difficulties. The high percentages in our data (66.7% and 45.3%, respectively) indicate that there are high chances that there is an increase in exposure intensity or that more hazardous operation conditions (such as; uncontrolled flaring, monitoring devices, etc.) prevail in the sampled communities, especially in Gbaramatu, Ogulagha, and Odimodi. Finally, these data reveal a stratified crisis: (i) behavioural (for example, lack of PPE and working long hours), (ii) spatial (for example, possibility to extend towards flaring zones), and (iii) systemic (for example, lack of engineering control and regulation). Together, they form an ideal storm of job-related toxicity. Not only is the effect physiological, but also economic and even generational: these workers (narrowly male and mostly aged 24-48, frequently working as breadwinners) are exposed to the steadily growing threat of developing chronic diseases, reduced efficiency, and a shorter lifespan caused by occupational hazards that may be freely avoided.

Biomarkers and PBPK Toxicokinetics: Confirming Internal Exposure and Systemic Risk

The biomonitoring data successfully retrieved in this research present a clear toxicologic conclusion that environmental and occupational exposures to crude oil-producing regions are indeed reflected in internal doses. Real-time biomarker measurements, coupled with physiologically based pharmacokinetic (PBPK) modelling, not only confirm exposure but also explain the behaviour of priority toxicants, such as benzene, lead, and polycyclic aromatic hydrocarbons (PAHs), regarding absorption, distribution, metabolism, and excretion (ADME). The levels of urinary trans,trans-muconic acids (t,t-MA), a tested and validated urinary biomarker of benzene exposure, were of serious concern, as depicted in Table 3, with a mean of 615.2±89.30µg/g creatinine within the cohort. This is many times higher than the ACGIH biological exposure index (BEI) of 500µg/g creatinine in workplaces. Interestingly, a considerable majority of the sampled workers (72.6%) surpassed this threshold, which is a significant indicator of exposure at chronic levels and hazardous exposure. These values are twice the ones described by an Indian study on petroleum workers exposed to gasoline vapours conducted by Mishra et al. in 2015 (mean t,t-MA values (in ~290–340 µg/g)). The conclusion is obvious: the levels of exposure in the Niger Delta are not only industrially important, but they are epidemiologically crucial. Mean blood lead, on the other hand, was 17.3±3.6 mcg/dL, and 83.4% of workers exceeded the CDC adult level of 5mcg/dL. When over 10 6g/ dL, lead, which is a neurotoxicant that is not biodegradable, causes multi-organ injuries, specifically hematopoietic and central nervous systems. The presence of almost all subjects at levels over three times the safe limit indicates continued exposure to water or through inhalation, as confirmed by the presence of lead in the groundwater at 0.092 mg/L (Table 1). Compared to the mean blood lead test results in Ebonyi State recorded by Onwuka et al.

(2019), which was 11.7 µg/dL in mineworkers, already deemed high, our data on the occupational lead load is among the highest ever observed in a Nigerian population. The point of verification for PAH exposure was the measurement of PAH-DNA adducts, with an average of 7.82±1.05 ng/mL in the cohort. More than 69.8% of all cases exceeded the internationally accepted limit of 4 ng/mL. Since PAH-DNA adducts serve as biomarkers of exposure and also reflect early events of genotoxicity and mutagenesis, these adducts indicate a pre-cancerous condition. This observation concurs with that of Ciarrocca et al. (2012), who reported high levels of PAH-DNA adducts (mean, 5.4 ng/ml) in coke oven workers in Italy. The observation that our oil field workers show higher levels than these numbers do presents a similar genotoxic environment, thus strengthening the carcinogenic risk profile.

To validate and predict the mechanism-based and simulated intracellular kinetics of these toxicants, PBPK modelling with PK-Sim 1 was applied (Table 4). The model for benzene was 9.4 µg/ml at 1.5 hours after exposure, with a biological half-life ($t_{1/2}$) of 10.3 hours. These kinetics match those reported by Zhu et al. (2013), who found a Cmax of 8.9 to 10.6 µg/mL and a $t_{0.5}$ of 8 to 12 hours in Chinese refinery workers. These confirmed kinetic parameters indicate that, in addition to the rapid absorption of benzene through inhalation, this chemical compound remains in the body for an extended period, allowing it to exert its cumulative toxicity, particularly in workers who experience frequent exposures during a 24-hour working cycle. In addition, simulation results indicated that repeated daily exposure results in toxicant accumulation, with subsequent exposures not reaching the previous baseline levels of plasma concentration before the next exposure. This reflects/indicates the bioaccumulation phenomenon at the low-elimination intervals, and compounds a systemic toxicant burden. Lead is no exception to this pharmacokinetic principle, and its biological half-life in blood is approximately 28-36 days, with a maximum of up to 25 years in bone. Therefore, the consistently high blood lead levels among our cohorts are not only reflective of past exposure but also of lifelong body burden that would take a long time to eliminate, even after the environment has been cleaned up. It is equally imperative to mention that though t,t-MA is regarded as one of the most probable biomarkers, it is affected by sorbic acid (a food preservative) and tobacco smoke. Ninety-two percent of our subjects were non-smokers, and confounding was avoided by controlling for dietary patterns through the use of a structured questionnaire. Additionally, further study in the future may provide more specificity in monitoring benzene, utilising S-phenylmercapturic acid (S-PMA) (Rappaport & Smith, 2010). However, in a high-exposure environment like ours, t,t-MA is valid and sensitive in terms of risk categorisation. The interaction of environmental and biological data, as modelled in this study, reveals a three-way exposure, absorption, and systemic effect pathway. The higher values of the biomarkers cannot be attributed to an artefact or mere confounding by lifestyle, but rather represent a record of environmental disregard and occupational risk.

Collectively, the data confirm the applicability of toxicokinetic models as predictive tools and validate the incorporation of such models into early warning systems, biomonitoring initiatives, and directed risk mitigation strategies.

Correlation, PCA, and Exposure Axes

Correlation analysis demonstrated a clear and strong association between environmental pollutants and biological responses. There was also a strong positive correlation between ambient benzene and urinary trans,trans-muconic acid ($r = 0.681$; $p < 0.001$), which confirms that environmental exposure directly reflects in the internal dose. This corresponds to the correlation proposed by Ibo et al. (2024), who found a comparable correlation ($r = 0.65$) among refinery workers in the United States. Similarly, the DNA adduct concentration showed modest results corresponding to soil benzo[a]pyrene levels ($r = 0.532$, $p = 0.001$), which confirms the results of an earlier study described by Perera et al. (2004) regarding PAH-linked genotoxicity. The correlation between blood lead and waterborne lead levels ($r = 0.497$, $p = 0.004$) suggested that ingestion was the primary route of exposure. Three unique exposure axes were obtained by the Principal Component Analysis (PCA), of which 90.5% of the total variance was explained. The component, majorly consisting of benzene, toluene and ethylbenzene, signified exposure to volatile organic compounds, i.e., VOC. Such an axis reflects international research, such as the one carried out by Rinsky et al. (1987) that linked the compounds to hematologic effects. The second component contained lead, cadmium and arsenic, which are signs of chronic exposure to heavy metals through ingestion and skin absorption. This observation is consistent with Zheng et al. (2019), who reported a similar toxicant cluster in smelting settings. The third group consisted of high-molecular-weight PAHs, such as BaP and chrysene, which represent carcinogenic soil-bound pollutants, a term also noted in Isangadighi and Ukudo (2025) and Tonne and Wilkinson (2013). Combining the correlation and PCA outcomes, a clear-cut toxicological framework has been put forward: VOCs are implicated in inhalation-related toxicity, metals are involved in systemic toxicity, and PAHs are associated with long-term mutagenicity. These groupings not only confirm the exposure pathways identified in this analysis but also align with the international literature. More to the point, they provide accurate targeting advice regarding mitigation, including airflow and flaring of VOCs, water treatment of metals, and soil correction of PAHs.

Toxicological Risk Quotients (RQ): Ranking the Health Threats

The quantitative assessment of the toxicity of exposure to environmental hazards under chronic exposure to chronic pollutants is presented by the Risk Quotient (RQ) approach to the toxicological risk assessment of the health hazard of environmental contaminants in the region where the crude oil considered in the present study is produced. RQ is computed

as the estimated exposure dose divided by the relevant reference dose (RfD), and values larger than 1.0 are commonly interpreted in environmental toxicology as indicating a possible adverse health impact, even without clinical manifestation. The RQ values were shocking in the case of multiple pollutants in this study (Table 11). In the case of Benzene, the RQ is 3.00, which means that ambient exposure and occupational exposure are greater than the U.S. EPA RfD of 0.004 mg/kg/day by a factor of 200%. It is not a peripheral overdose; it is toxicological evidence of systemic overexposure. When the current finding is compared with the result of previous researchers Oghenero et al. (2020) who documented average of 2.67 RQ level of benzene in the gas-flaring sites of Bayelsa State, our finding may be linked to the deteriorating exposure status of residents, particularly during the dry seasons when the highest concentration of 124.3ug/m^3 of benzene was documented (Table 1). The situation with lead was even worse, with the RQ of 3.75 that vastly exceeds the index of 1.0. This implies that estimated levels of dietary exposure and groundwater consumption of lead are 275% higher than the tolerable level (RfD: 0.0035 mg/kg/day). These elevated RQs have important consequences on both a biological and clinical level, given that the blood lead levels of our cohort had an average of 17.3±3.6 microg/dL (Table 3), which is significantly above the current reference level of 5 microg/dL set by the CDC for adults. In a comparative analysis, Njoku et al. (2022) noted RQs of 1.8 to 2.2 as the lead in clean, drinkable water in oil-producing areas of Imo State. We are at least one and a half times more likely, which means there is more severe contamination and it requires urgent remediation.

Another carcinogen of Group 1 and a reported endocrine disrupter, arsenic, registered an RQ of 3.00, which means a threefold overstatement of the RfD (0.0003 mg/kg/day). The result aligns with those of Uhegbu et al. (2012), who reported arsenic RQs ranging from 2.4 to 2.9 in their boreholes in the Ogoni area. The fact that such high RQs are consistently reported among independent studies in the Niger Delta would indicate a systematic weakness in groundwater protection, which has been brought about by decades of pipeline corrosion, underground contamination, and unsuccessful containment of drilling fluids. Cadmium and benzo[a]pyrene (BaP), on the contrary, were not detected at RQ above 1.0, and those were 0.70 and 0.43 consecutive decimals, respectively. These imply reduced short-term risk at the prevailing exposure. Nevertheless, it is essential to perceive these values relative to one another. Cadmium is a bioaccumulative nephrotoxin; at sub-threshold exposure doses, chronic exposure may accumulate in kidney tissue and result in irreversible damage. Similarly, although BaP has a relatively low RQ, it is a highly potent polycyclic aromatic hydrocarbon commonly known to cause genotoxic and carcinogenic effects, especially when it combines with other PAHs and soot particles generated during flaring processes. Therefore, their separate RQs might not be of concern regarding acute intervention levels; however, these add up to the total toxic burden that can commonly be

ignored in linearised risk calculations, but is well understood in environmental medicine (see Viegas et al., 2015).

Moreover, given that these pollutants are perceived not in isolation but in complex interactions, their toxicodynamics is even more evident. Certain compounds, such as benzene, enhance the hematotoxic effect of lead and cadmium and can inhibit the hepatic detoxification pathways that are essential for the metabolism of PAHs. Such an issue of multiplicative risk situation, which is not considered in classical RQ models, makes the impact on public health considerably higher than the actual values of the particular RQs might indicate. Another important aspect of this study is the spatial risk distribution, where the Gbaramatu and Ogulagha locations consistently yielded the best results for all analytes. These are places of high flaring intensity, where groundwater turnover is significantly low and engineering controls are weak, all of which constitute a clear geospatial epicentre of toxic risk. Comparatively, Bonny, where engineering controls had operated with relatively higher levels of effectiveness (59-64%), had relatively low values of pollutants and hence RQs, supporting the critical role of engineering infrastructure in exposure control mechanisms. Based on these results, the conclusion is grim: three out of six studied pollutants are characterised by a high non-carcinogenic risk (RQ more than 1), and all six have a chronic toxicity profile. The lack of working gas detectors (Table 9), ineffective PPE use (Table 2), and high biomarker levels (Table 3) are additional confirmations that toxicant exposure is indeed present, biologically active, and accumulating to an avoidable dose. Finally, the RQ analysis does not just show a snapshot of risks. Still, an objective, numerically ordered mandate on what needs to be addressed first in terms of remediation and risk reduction. Exposure to benzene, lead, and arsenic must be addressed simultaneously in any site-specific intervention plan. Besides, these RQs provide a strong foundation on which risk communication can be conducted with policymakers, those impacted by the risk, as well as industry players, as they seek to translate scientific data that is often complicated into real, actionable priorities.

Engineering Failures: Systemic and Chronic

The engineering examination presented in this paper has revealed a characteristic engineering course of action failure, which forms an immediate multiplier of risks to both environmental and occupational safety and health in crude oil-producing areas. The outcomes of the Failure Mode and Effects Analysis (FMEA) (Table 5) do not allow any misunderstanding: the rupture of the pipeline (RPN = 250), malfunctioning of the gas detectors (RPN = 216), failure of the flare stack (RPN = 200) are at the top of the list of critical risks. With these risk priority numbers (RPNs) exceeding 150, these systems are catastrophically vulnerable. The RPN of 250 related to pipeline rupture is quite incriminating. The pipelines are the arteries of the oil distribution system, and their breakdown leads to the massive release of hydrocarbons, accompanied by the outbreak of

fire, vapour inhalation, soil and groundwater contamination, and atmospheric pollution. This conclusion is supported by Eregha & Irughe (2009) who confirmed that over 60% of the number of reported oil spills in Niger Delta between 1999 and 2008 were as a result of pipeline failure. As our RPN reveals, this engineering Achilles heel remains unrepaired to this day, more than ten years later. As primary defence measures, gas detectors, which are meant to serve as a warning to personnel of volatile organic compound (VOC) leakages, were non-functional or delayed with an RPN of 216. This is also in line with the Environmental Assessment of Ogoniland (UNEP, 2011), which reported that most of the gas monitoring systems within Nigerian facilities were either switched off or not connected to alarm systems.

In a place where the level of benzene is 124.3 mg/m³ (Table 1), which is almost eight times the recommended standard by WHO, the lack of decent gas detection becomes a long-overdue death sentence. Flare stack failures (RPN = 200) denote a degradation of the system, the absence of precautionary maintenance, and neglect of operations. The use of flare stacks was either very unstable (frequently flared, more than a designed limit) or occurred with irregular combustion, emitting unburnt hydrocarbons and high-molecular-weight PAHs into the environment in most of the facilities evaluated. Our environmental evidence supports this: our environmental samples of benzo[a]pyrene (BaP) concentration are 5.81 μg/kg (Table 1), and the abnormally high DNA adducts among affected workers support our finding that incomplete combustion and dispersal of PAH as an aerosol must have occurred. This operational lapse has been repeatedly highlighted in the literature. It was observed that 78% of flare stacks in Delta State were discharging pollutants outside their design capacity due to poor burners and burners incorrectly vented to an inadequate height (Ikhuoria et al., 2020). All these are compounded by site-specific engineering evaluation (Table 9). The results at Gbaramatu were appalling: less than half of the areas checked had gas detectors (41%), SCADA systems (43%), and pressure valves (46%). This translates to over 50% of engineering controls, which are either not working or are unreliable, in an area where labourers breathe carcinogenic VOC and consume water contaminated with lead. Such figures are shockingly low compared to Bonny, where, despite less-than-ideal systems, a score of above 59% was achieved in functional systems, especially due to the international enforcement of standards carried out by Shell. Such a discrepancy highlights the notion that there are quantitative safety benefits to subjecting foreign operators to international pressure for compliance, and conversely, that in the absence of a compliant jurisdiction, indigenous operators allocate disproportionately low funds to critical safety infrastructure elements.

Moreover, these breakdowns are not merely mechanical, but also regulatory. Both the Department of Petroleum Resources (DPR) and the National Oil Spill Detection and Response Agency (NOSDRA) in Nigeria have repeatedly failed to meet minimum safety standards. Although there are good technical standards, such as API RP 752 and OSHA

1910 standards, that can serve as benchmarks for mitigating hazards, their usage in the Niger Delta is practically zero. This lack of governance means that flare stacks can go uncontrolled, pipes can be left in a deteriorated state without cathodic protection, and gas sensors can remain unfixed for years. In the absence of strict regulation, engineering failures become the norm, eventually leading to deadly consequences. The lack of systemic oversight will result in the fact that even the soundest program in the area of toxicology or biomonitoring will be fatally compromised. No surveillance and early identification can replace or counter an unprevented gas leakage, not a sealed rupture, or an unfocused worker. The engineering control hierarchy, which begins with elimination and substitution and progresses to PPE, requires functional levels. In this case, three of the four highest tiers of the hierarchy collapsed, and only PPE, which is inconsistently applied in our findings (Table 2), remains to stop the invading force. To conclude, the engineering infrastructure at such crude oil plants is not only inefficiently fulfilling its task. Still, it is also structurally unsound, presenting an existential threat to both human and environmental health. As long as such breakdowns are not rectified by legally binding activities, such as identification and recapitalisation, third-party assessment, and cross-national compulsion to conformity, the loop of exposure, disease, and contamination will continue without restraint.

CONCLUSION

This paper concludes that the exploitation of crude oil in the Niger Delta region is linked to high levels of environmental and occupational health risks, which are supported by elevated concentrations of pollutants, biomarkers, and impending failures of engineering systems. Through an integrated toxicokinetics and engineering-based assessment method, the data demonstrate alarming levels of benzene, lead, and PAHs in the environment, as well as equally high biomarkers in exposed oilfield workers, which in many cases exceeded internationally agreed-upon biological exposure indicators. The PBPK modelling confirmed systemic absorption and bioaccumulation processes, while the engineering check tests revealed a lack of essential safety systems, including gas sensors, pressure valves, and pipeline structural integrity. Possible exposures to benzene, arsenic, and lead were also identified as priority risks, with RQs exceeding 3.0 for each. Taken together, the study not only reveals a toxicological crisis but also provides a scientifically based rationale for immediate intervention across the fields of toxicological risk, environmental monitoring, and industrial engineering control.

Recommendations

To address the identified risks, a multi-pronged action plan is highly advisable to be undertaken immediately. The priority should be given to implementing predictive maintenance systems in the oil complex, utilising extensive engineering controls based on

SCADA systems, and enforcing the mandatory use of personal protective equipment (PPE) policies with the assistance of regular occupational safety audits. Regulatory bodies, such as DPR and NOSDRA, should be mandated by law to install real-time monitoring systems and conduct third-party audits to verify the integrity of gas detectors, pressure relief valves, and flare stacks. In addition to this, toxicokinetic modelling and biomonitoring must also be established as an integral part of occupational health monitoring, with intervals of biological monitoring for workers at risk using established biomarkers, including t,t-muconic acid, S-PMA, and PAH-DNA adducts. The immediate solution should be environmental clean-up, the availability of clean water, and access to healthcare in affected communities located near flare points, and standards of international practice, like OSHA 1910, ISO 45001 and WHO IPCS guidelines should be aligned during the implementation of regulatory enforcement to drive sustainable reduction of hazards and environmental justice in the Niger Delta.

Declaration Statements

a. **Ethical Clearance:** The research adhered strictly to ethical guidelines and standards to maintain integrity and credibility. Participants were fully informed of the study's purpose, and written consent was obtained before data collection.

b. **Author Contributions:** Ubong Bernard Essien conceived and designed the study, developed the integrated toxicokinetic and engineering-based framework, and led the drafting of the manuscript and its critical revision. Smart Acha contributed to the design of the toxicological risk assessment, performed statistical analysis, and supported the interpretation of the analytical results. Ernest N. Orhuebor coordinated environmental field sampling and analysed pollutant pathways. Felix Isidore Ibanga conducted the occupational hazard evaluation and provided engineering insights for mitigation planning. Uduak Isidore Udoh assisted with literature synthesis, hazard categorisation, and discussion development. Patience Oinu Momoh coordinated field operations, respondent engagement, and ensured ethical compliance. Blessing Ukudo organised research documentation, referencing, and ensured overall manuscript consistency. Prince Uche Michael contributed to the methodological framework, supported exposure modelling, and handled technical proofreading and formatting.

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f. **Availability of Data and Materials:** The datasets generated and analysed during the current study are available upon reasonable request from the corresponding author. All materials used have been appropriately cited and referenced.

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