Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Application of Tier 2 Site-Specific Target Levels (SSTLs) for Certification and Close-Out of Hydrocarbon-Contaminated Soil at MOGHO, Bodo Community, Niger Delta

Suleiman Abba

Suleiman.abba@strath.ac.uk

University of Strathclyde

Charles Knapp

University of Strathclyde

Research Article

Keywords: Site-specific target levels (SSTL), risk-based corrective action (RBCA), petroleum hydrocarbons, contaminated land, Niger Delta, certification and close-out, TPHCWG, human health risk assessment

Posted Date: November 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11153720/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Application of Tier 2 Site-Specific Target Levels (SSTLs) for Certification and Close-Out of Hydrocarbon-Contaminated Soil at MOGHO, Bodo Community, Niger Delta

*Suleiman Abba[1] and Charles Knapp[1]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XQ, United Kingdom

Correspondence: Suleiman Abba, Suleiman.abba@strath.ac.uk

Charles Knapp, charles.knapp@strath.ac.uk

Abstract

Certification and close-out of petroleum-contaminated sites in Nigeria often rely on fixed, generic regulatory thresholds that may not adequately reflect site-specific exposure conditions, contaminant behaviour, land use or receptor sensitivity. This creates uncertainty in residential or subsistence settings, where numerical compliance alone may not demonstrate protectiveness. This study addresses this gap by using a petroleum-contaminated site at MOGHO, Bodo Community, as a demonstration case for applying Tier 2 Site-Specific Target Levels (SSTLs) to support risk-based certification and close-out of petroleum-contaminated soil in Nigeria. The study links measured residual petroleum contamination with receptor-specific exposure pathways, petroleum hydrocarbon fractionation, cumulative human health risk and residential close-out decision-making within a Nigerian contaminated-land context. Measured concentrations of total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) in surface soil were assessed using a tiered human health risk assessment framework. Tier 2 modelling was conducted for child and adult upper-percentile residential receptors, considering soil ingestion, dermal contact with soil, vegetable ingestion and inhalation of outdoor air.

The results showed that carcinogenic risk exceeded the adopted target level of 1.0×10^{-6}, with estimated risks of 3.4×10^{-6} for the child resident, 1.2×10^{-5} for the adult resident, and 1.5×10^{-5} for the combined residential receptor. Non-carcinogenic hazard indices also exceeded the acceptable threshold of 1.0, with values of approximately 33 for the child resident and 15 for the adult resident. Vegetable

ingestion was the dominant exposure pathway for both risk endpoints, while PAHs mainly drove carcinogenic risk and heavier aromatic TPH fractions dominated non-carcinogenic hazard. The original TPH concentration of approximately 3,900 mg/kg exceeded the calculated TPH concentration at SSTL of approximately 110 mg/kg, requiring a reduction of about 97% to achieve the modelled site-specific target condition. Overall, the findings indicate that the current soil-source condition does not support unrestricted residential certification under the modelled exposure assumptions without further remediation, exposure-pathway control, land-use restrictions, or defensible refinement of the conceptual site model.

Keywords: Site-specific target levels (SSTL); risk-based corrective action (RBCA); petroleum hydrocarbons; contaminated land; Niger Delta; certification and close-out; TPHCWG; human health risk assessment.

1. Introduction

1.1 Background to petroleum-contaminated land in Nigeria

Hydrocarbon-contaminated land remains one of Nigeria's most persistent environmental management challenges, particularly in the Niger Delta, where decades of oil exploration, production, pipeline failures, illegal refining, and spill incidents have widely contaminated soil, groundwater, surface water, sediments, wetlands, and agricultural land. The United Nations Environment Programme's Environmental Assessment of Ogoniland found that hydrocarbon contamination in parts of Ogoniland was extensive, affecting soil and groundwater and posing a long-term risk to human health, ecological systems, and local livelihoods [40]. UNEP further described the restoration of Ogoniland as a potentially long-term, wide-ranging cleanup effort because of the scale and persistence of contamination across multiple environmental media [40].

A major difficulty in contaminated land management is determining when a remediated site is genuinely safe for certification and close-out. In Nigeria, hydrocarbon-contaminated sites have historically been assessed against generic regulatory criteria, including target and intervention values for mineral oil or total petroleum hydrocarbons [14]. The commonly cited Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) approach uses a target value of 50 mg/kg and an intervention value of 5,000 mg/kg for TPH in soil, but these values do not fully account for site-specific land use, exposure pathways, receptor characteristics, hydrogeological conditions, or the chemical composition of the petroleum release [13]. This means that compliance with a generic intervention value may not, by itself, demonstrate protectiveness under a sensitive residential or subsistence exposure scenario.

Petroleum hydrocarbon contamination is chemically complex. It may include TPH fractions, volatile compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX), and PAHs such as naphthalene, phenanthrene, benzo(a)pyrene, and dibenz(a,h)anthracene. These contaminants differ substantially in volatility, solubility, sorption behaviour, mobility, biodegradability, persistence and toxicity. For this reason, modern petroleum risk assessment increasingly evaluates TPH by carbon number and chemical class, rather than treating TPH as a single contaminant [18, 30, 31].

To address this limitation, this study uses the MOGHO site as a demonstration case to evaluate how Tier 2 SSTLs can support risk-based certification and close-out decisions for petroleum-contaminated soil in Nigeria. The contribution lies not only in the site-specific results, but in demonstrating a reproducible decision workflow that links secondary regulatory datasets, fractionated petroleum chemistry, source–pathway–receptor assessment, receptor-specific exposure assumptions, cumulative risk estimation and verification requirements. The specific objectives are to identify the contaminants of concern, develop a CSM, assess carcinogenic and non-carcinogenic risks for residential receptors, derive Tier 2 SSTLs where acceptable risk criteria are exceeded, compare measured concentrations with calculated SSTLs, and evaluate whether SSTL-based outputs provide a more defensible basis for certification than fixed generic TPH thresholds alone.

The study is guided by the hypothesis that generic petroleum hydrocarbon criteria, when used in isolation, are insufficient to determine whether a remediated petroleum-contaminated site is safe for certification and close-out under site-specific exposure conditions. The null hypothesis is that there is no meaningful difference between closure decisions based on fixed generic TPH target/intervention values and those based on site-specific risk assessment and SSTLs. The alternative hypothesis is that SSTL-based assessment provides a more protective and scientifically robust basis for certification because it accounts for land use, receptor characteristics, exposure pathways, contaminant toxicity and site-specific environmental conditions. Accordingly, we evaluated the acceptability of residual contamination at the study site by comparing estimated carcinogenic risks and non-carcinogenic hazard indices with defined target criteria.

2. Study Area and Site Description

2.1 Location and land-use setting of the study area

The site is a hydrocarbon-impacted location in MOGHO, Bodo Community, in Gokana Local Government Area of Ogoniland, Rivers State, Nigeria, with reference coordinates: Easting 308896, Northing 513037 (WGS 84; Zone 32N). Ogoniland is one of the most widely documented hydrocarbon-contaminated areas in the Niger Delta, where historical oil exploration, pipeline operations, and spill incidents have widely contaminated different environmental media [40]. Site data indicate that the

area is situated within a local setting influenced by petroleum infrastructure, including a pipeline right-of-way that traverses the area. The pipeline corridor provides useful site context because it may represent a potential pathway for petroleum release, consistent with documented pipeline-related contamination concerns in the Niger Delta [40].

Site reconnaissance and field observations indicate mixed surrounding land use, including nearby homes, informal access routes, and agricultural activities. The presence of community receptors and vegetable farming areas makes the site relevant for residential and subsistence exposure assessment. These land-use conditions indicate that potential exposure may occur through direct contact with contaminated surface soil and through consumption of home-grown vegetables, particularly where local residents depend on small-scale farming for food and livelihood. Therefore, the site represents a sensitive exposure setting in which child and adult residents may be exposed through soil ingestion, dermal contact, ingestion of vegetables grown in affected soil and inhalation of outdoor air.

This setting makes the site a suitable case study for evaluating risk-based certification and close-out because it combines residual petroleum hydrocarbon contamination, sensitive residential receptors, potential food-chain exposure, and the need to determine whether calculated SSTLs provide a defensible basis for residential close-out and long-term land reuse.

2.2 Conceptual site model (CSM)

Although conceptual site models are a standard component of risk-based contaminated-land assessment, they are less consistently documented in Nigerian petroleum-contaminated site closure practice, where decisions often rely on generic concentration thresholds. In the Niger Delta context, an explicit CSM is therefore useful because it makes the source–pathway–receptor assumptions transparent and links the measured contamination to the exposure scenarios used for SSTL derivation [7].

The CSM for the study area was developed to identify the relevant source–pathway–receptor linkages controlling potential human exposure to residual petroleum hydrocarbons in the 0–1 m surface-soil interval, as shown in Table 1 and Fig. 1. This interval was selected because it is most accessible to residents and most relevant to

direct contact and plant uptake. The CSM treats the soil source as a petroleum mixture comprising PAHs, VOCs/BTEX, MTBE, and aliphatic and aromatic TPH fractions, with the detailed analytical grouping and individual compounds described in Section 3.1.

The CSM identifies child and adult residents as the primary human receptors under a conservative residential exposure scenario. The relevant exposure pathways include direct contact with impacted soil and indirect exposure through the soil–plant–human pathway. Table 1 summarises these source–pathway–receptor linkages, while Sections 3.2 and 3.3 describe the receptor assumptions and exposure pathway selection in detail.

The CSM also provides the basis for evaluating carcinogenic risk and non-carcinogenic hazard as the main risk endpoints. These endpoints were used to determine whether the identified exposure linkages required further risk-based evaluation, while Section 3.6 presents the detailed risk criteria and equations.

Table 1 Source–Pathway–Receptor Linkages

Source	Pathway	Receptor	Status
Contaminated surface soil	Dermal contact, ingestion, inhalation	Residents, farmers, children, shortcut users	Complete
Contaminated soil	Crop uptake	Subsistence crop consumers	Complete
Contaminated grass/soil	Grazing	Livestock and indirect human consumers	Complete
Petroleum vapours	Vapour intrusion/inhalation	Nearby residents	Potentially complete
Groundwater plume	Discharge to surface water	Surface water/ecological receptors	Not considered

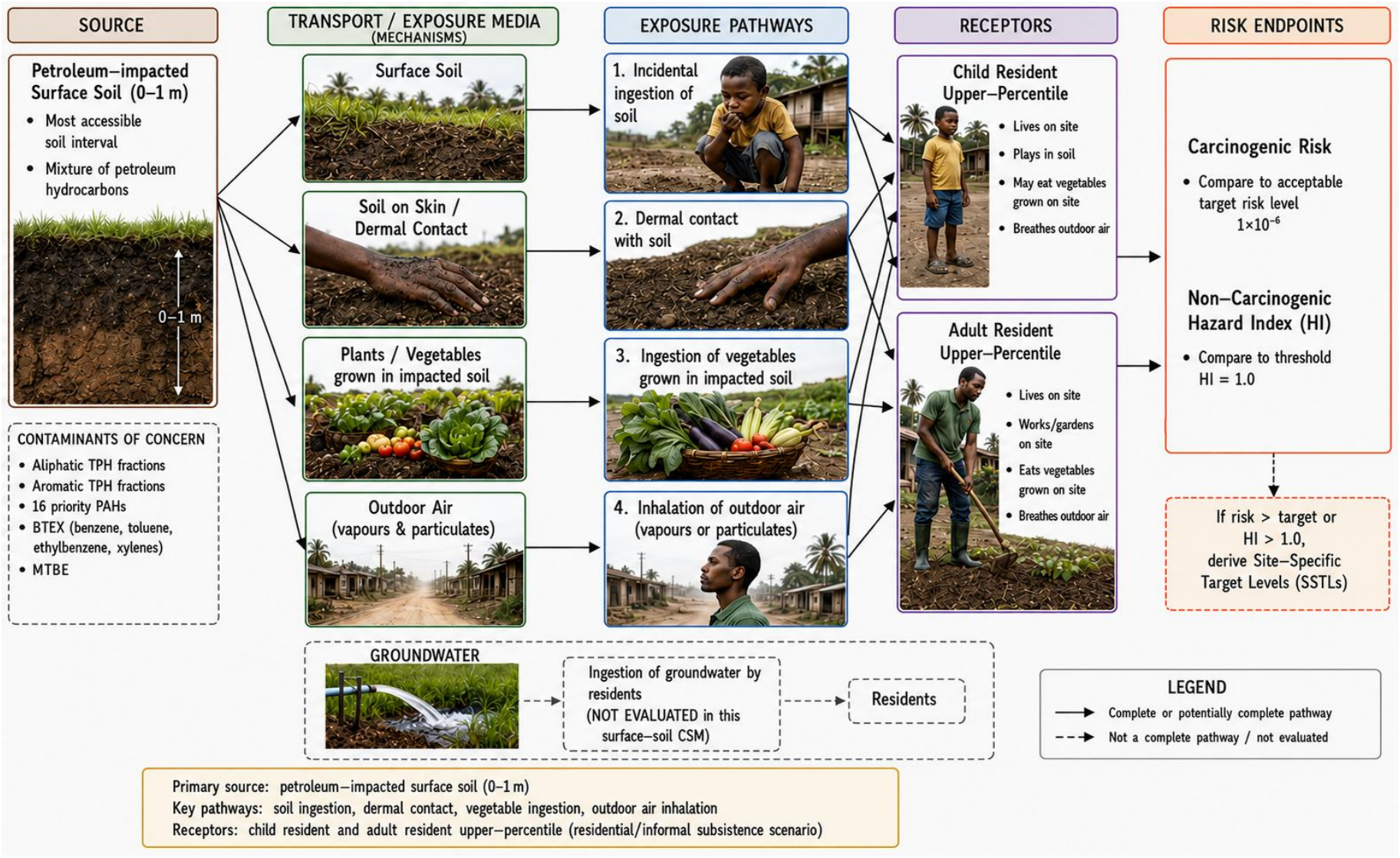


Fig 1 Conceptual Site Model of the study area

3. Materials and Methods

3.1 Data source and analytical dataset

This study used an existing analytical dataset of previously measured surface-soil concentrations obtained from the National Oil Spill Detection and Response Agency (NOSDRA). The dataset was used as secondary analytical data for the Tier 2 human health risk assessment and SSTL derivation. No new laboratory analysis was undertaken as part of the RISC5 modelling stage; rather, the NOSDRA dataset was organised, analysed, checked and processed for risk assessment modelling.

The dataset comprised petroleum-related contaminants grouped into three main categories: polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), including BTEX and MTBE, and Total Petroleum Hydrocarbon Criteria Working Group (TPHCWG) fractions. Reported concentrations were checked for consistency of units, expressed in mg/kg for soil, and arranged into RISC5-compatible input groups. Where multiple measured values were available, 95% upper confidence limit values were calculated using ProUCL Version 5.1.002 software and used as representative model-input concentrations for the soil source. Supplementary Data S1 and S2 provide the full RISC5 modelling output used for the Tier 2 risk assessment and SSTL derivation, respectively.

The PAH dataset included low- and high-molecular-weight compounds, including naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenz(a,h)anthracene and benzo(g,h,i)perylene. These compounds were retained because they are petroleum-related contaminants of concern and include carcinogenic PAHs relevant to residential human health risk assessment [12, 28].

The VOC dataset included benzene, toluene, ethylbenzene, xylene isomers and methyl tert-butyl ether (MTBE). These compounds were assessed because they are common petroleum-related constituents characterised by relatively high volatility and, particularly for benzene, toluene, and MTBE, greater environmental mobility than heavier hydrocarbon fractions. Their inclusion allowed the assessment to consider potential risks associated with lighter petroleum components and inhalation of outdoor air [16, 21, 41, 42].

The TPHCWG dataset included aliphatic and aromatic hydrocarbon fractions across defined equivalent carbon ranges (Twerdok, 1999). The aliphatic fractions included C5–C6, C6–C8, C8–C10, C10–C12, C12–C16 and C16–C35, while the aromatic fractions included C7–C8, C8–C10, C10–C12, C12–C16, C16–C21 and C21–C35. The measured concentrations were used as model inputs for human health risk assessment and SSTL derivation under the selected residential exposure scenario. The risk-based approach follows the principle that site assessment and corrective action should protect human health and the environment [6, 8]. Section 3.1.1 summarises the available analytical data-quality information for this dataset.

3.1.1 Data Quality and Analytical Reporting

Soil sampling was undertaken from five monitoring boreholes at depths of 0.5, 1.0, 4.0, 7.0 and 10.0 m. The sampling protocol followed ISO 18400 soil sampling standards and U.S. EPA-based methods, with soil descriptions recorded in accordance with BS 5930. During sampling, lithology was logged in situ, and olfactory and sheen observations were used as field indicators of hydrocarbon presence. Soil samples were collected into appropriate containers, labelled, stored in cool boxes with ice packs and transferred for laboratory analysis. Measures were taken to minimise cross-contamination, including using appropriate sample containers, preserving samples, field logging, sample coding, and decontaminating equipment with 95% ethanol.

The laboratory report provided numerical limits of detection and accreditation status for the measured analytes. Speciated PAHs in soil were reported with a limit of detection of 0.05 mg/kg, while TPHCWG aliphatic and aromatic fractions had fraction-specific limits of detection ranging from 0.01 to 10 mg/kg, depending on the carbon range. VOCs, including MTBE, benzene, toluene, ethylbenzene and xylene isomers, were reported in µg/kg, with limits of detection of 5 µg/kg for most VOCs and 8 µg/kg for p- and m-xylene. The PAH, VOC and fractionated TPH analyses were reported as ISO 17025 accredited

The analytical methods included GC-MS analysis for speciated PAHs (U.S. EPA 8270), headspace GC-MS analysis for VOCs/BTEX (U.S. EPA 8260), and GC-FID/GC-MS methods for petroleum hydrocarbons with carbon banding. The TPHCWG fractionation data used in the RISC5 model were therefore supported by laboratory-

reported method descriptions, accreditation status and numerical detection limits. Soil analytical results were reported on a dry-weight basis, with moisture correction applied where required.

3.2 Exposure Scenarios and Receptors

The exposure assessment considered upper-percentile residential receptors because the site is located in a setting where residential occupation, informal land access and potential subsistence activities may occur. The assessment evaluated three receptor scenarios: Child Resident – Upper Percentile, Adult Resident – Upper Percentile, and a combined residential receptor in which child and adult risks were added together. This approach allowed the assessment to evaluate both age-specific exposure and cumulative residential exposure over time [29, 36].

The Child Resident – Upper Percentile receptor represents a conservative estimate of exposure for children living in or near the petroleum-impacted area. Children were included because they may experience greater exposure relative to body weight and are generally important receptors in residential human health risk assessment [38]. The Adult Resident – Upper Percentile receptor represents long-term adult exposure under residential land-use conditions [37].

The combined residential receptor represents cumulative exposure across child and adult life stages. This approach is appropriate for carcinogenic risk assessment because cancer risk is generally evaluated over a lifetime and may accumulate across different exposure periods. Therefore, adding child and adult receptor risks provides a more complete estimate of lifetime residential carcinogenic risk [10, 33, 35]

The term “upper-percentile” indicates that the receptor represents a conservative, high-end exposure scenario rather than an average condition. Human health risk assessment commonly uses high-end or reasonable maximum exposure scenarios to protect individuals at the upper end of the exposure distribution without relying solely on extreme worst-case assumptions [39]. In the RBCA framework, receptor selection and exposure assumptions are central to deriving protective risk-based screening levels (RBSLs) and SSTLs [5, 6, 8]. For this study, upper-percentile residential receptors were selected to provide a conservative assessment of potential exposure under a sensitive residential land-use scenario and to inform certification and site close-out decisions.

3.3 Exposure Pathways

The exposure pathways modelled for the site were ingestion of soil, dermal contact with soil, ingestion of vegetables, and inhalation of outdoor air. These pathways were selected from the CSM because residential and subsistence exposure to petroleum-impacted surface soil may occur. In human health risk assessment, exposure pathways are considered complete when a contaminant source, environmental fate or transport pathway, exposure point, exposure route, and receptor are present [15, 33, 38].

Ingestion of soil was included because residents may accidentally ingest contaminated soil or dust during outdoor activities. This pathway is relevant to residential settings where surface soil remains accessible. Dermal contact with soil was included because residents may come into direct skin contact with contaminated soil during domestic, recreational, farming or informal land-use activities.

Ingestion of vegetables was included because the site occurs within a mixed residential and agricultural setting where vegetable cultivation or subsistence gardening may occur. This pathway represents the potential transfer of contaminants from soil into edible plant tissues, followed by human consumption. Including it matters because petroleum-related contaminants may contribute to exposure through the soil–plant–human pathway, particularly in communities where locally grown produce forms part of the household food supply. Risk assessment guidance recognises that consuming home-grown produce can be a relevant exposure route in residential or agricultural land-use scenarios [8, 37].

Inhalation of outdoor air was included to assess whether volatile emissions from contaminated soil meaningfully contribute to human health risk [22]. This pathway is relevant for volatile petroleum constituents such as BTEX and MTBE, which may partition from soil into air [2, 17]. Although heavier TPH fractions and PAHs are generally less volatile, inclusion of this pathway allowed the model to confirm whether inhalation of outdoor air was a significant driver of risk.

3.4 Exposure Parameters and Model Assumptions

Exposure parameters were specified in RISC5 to represent the residential informal and subsistence exposure scenario defined for the study area. The parameters

represent upper-percentile child and adult residential receptors and provide a conservative basis for estimating carcinogenic risk, non-carcinogenic hazard, and SSTLs. Table 2 summarises the specific exposure parameters used in the model.

323 **Table 2** Specific exposure parameters used for RISC5 modelling

Parameter	Child Resident – Upper Percentile	Adult Resident – Upper Percentile	Justification
Averaging time for carcinogens (yr)	70	70	Lifetime averaging period for carcinogenic risk assessment [1].
Body weight (kg)	17.2	64	[3,20, 24].
Exposure duration (yr)	6	45	Conservative assumption that residents, including the farm-working population, are likely to spend most of their life in the same area
Exposure frequency for soil (events/yr)	350	350	Assumed to be 350 days per year for adult and child receptors due to regular community use of the link path
Skin surface area exposed to soil (cm^2)	2190	5300	RISC5 Default Value
Soil/skin adherence factor (mg/cm^2)	0.2	0.07	RISC5 Default Value
Ingestion rate for soil (mg/day)	200	100	RISC5 Default Value
Exposure frequency for vegetable intake (events/yr)	350	350	Assumed regular consumption exposure under residential informal and subsistence conditions
Ingestion rate for above-ground vegetables (g/day)	55.8	127	RISC5 Default Value
Ingestion rate for root vegetables (g/day)	48.5	87.5	RISC5 Default Value
Fraction of vegetables grown in contaminated soil (-)	0.25	0.25	Conservative assumption for partial contribution of locally grown produce
Exposure frequency for outdoor air (events/yr)	350	350	Assumed regular outdoor exposure under the residential informal scenario
Inhalation rate outdoors (m^3/hr.)	1.2	1.6	RISC5 Default Value
Time outdoors (hr./day)	10	15	Conservative outdoor activity assumption for the selected receptors

324

As shown in Table 2, the same annual exposure frequency of 350 events/year was applied to soil contact, vegetable intake and outdoor-air exposure for both receptor groups. This reflects the conservative assumption that residents and farm-working community members may regularly use or occupy the affected area. We used exposure duration, body weight, soil ingestion rate, dermal parameters, vegetable ingestion rates, and outdoor inhalation parameters to define receptor-specific exposure under the selected residential informal and subsistence scenario.

For the vegetable ingestion pathway, the model assumed that a fraction of consumed vegetables could be grown in impacted soil and that petroleum-related contaminants may transfer from root-zone soil into edible plant tissues. For outdoor-air exposure, volatile constituents were considered capable of partitioning from soil to air, while heavier TPH fractions and PAHs were expected to contribute less because of their lower volatility. These assumptions were applied as conservative screening-level inputs rather than site-specific behavioural measurements, and the resulting model outputs were interpreted as health-protective estimates for certification and close-out decision-making.

3.5 Soil, Source Geometry and Transport Model Parameters

Soil, source geometry and transport parameters were specified in RISC5 to represent the physical conditions controlling contaminant partitioning, volatilisation, leaching and plant uptake from the soil source. These parameters differ from receptor exposure parameters because they describe the environmental medium, source configuration, and transport setting the model uses. Table 3 summarises the selected soil and transport inputs used for the study area.

354 **Table 3.** Soil and transport parameters used for RISC5 modelling

Parameter	Value	Unit	Source/basis
Total porosity	0.481	cm^3/cm^3	RISC5 Default value for silty clay
Residual water content	0.09	cm^3/cm^3	RISC5 Default value for silty clay
Fraction organic carbon	0.002	gOC/gsoil	RISC5 Default value for silty clay
Soil bulk density	1.4	g/cm^3	RISC5 Default value for silty clay
Saturated conductivity of vadose zone	0.1	m/day	RISC5 Default value for silty clay
Van Genuchten N parameter	1.09	-	RISC5 Default value for silty clay
Infiltration rate	30	cm/year	RISC5 model input
Depth to top of contamination	1	m	Site-specific data
Length of source area	60	m	Site-specific data
Width of source area	50	m	Site-specific data
Thickness of contamination	1	m	Site-specific data
Distance from bottom of source to groundwater	4.83	m	Site-specific source geometry input
Outdoor-air box height	2	m	Assumed/model input values.
Outdoor-air box width	10	m	Assumed model input values
Outdoor-air box length	10	m	Assumed model input values
Wind speed	2.1	m/s	Literature value

As shown in Table 3, the soil medium was represented using silty clay properties from the RISC5 soil property database, justified by the Lithostratigraphic units showing the localised geology of the study area (Fig. 2), while the source geometry parameters defined the position and dimensions of the contaminated soil source. These inputs were used to estimate contaminant movement from the soil source and potential exposure through the selected pathways.

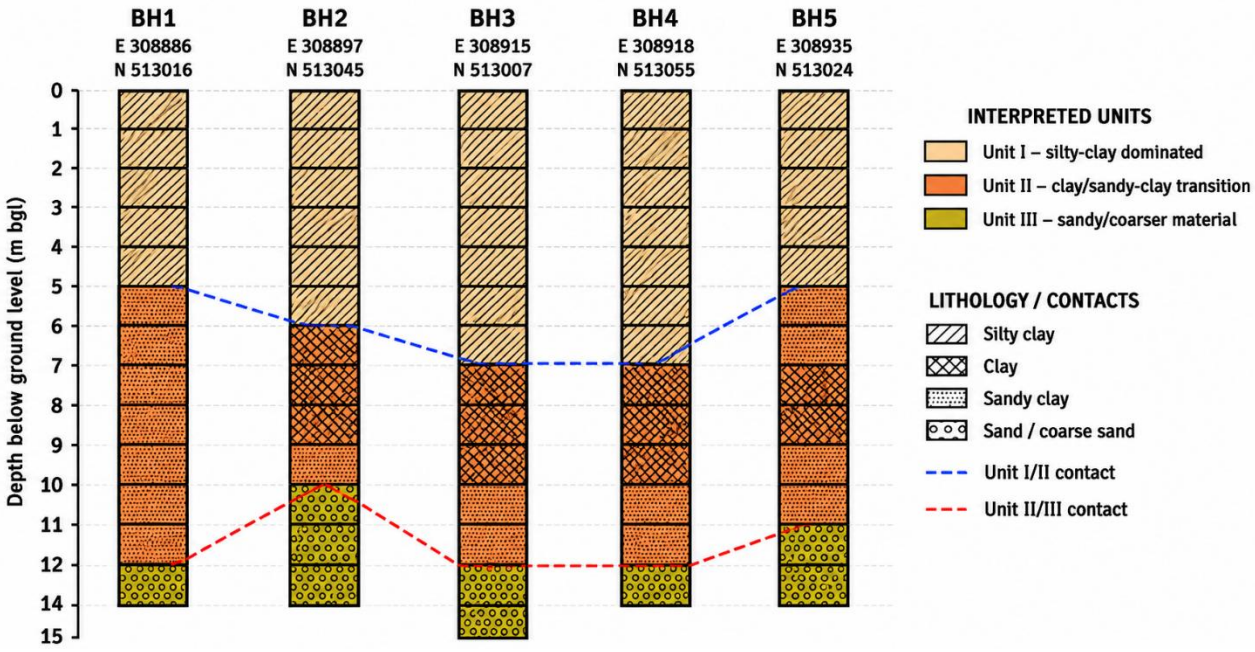


Fig. 2 Local lithostratigraphic correlation of the study area

Notes:

- *Colours denote the three interpreted local units; hatch patterns reproduce the lithologic interval*
- *Unit contacts are correlation-inferred from the supplied field descriptions and are not stratigraphic boundaries.*

Plant uptake was also included because vegetable ingestion was one of the complete exposure pathways in the CSM. RISC5 used the Trapp and Matthies plant uptake model to represent the transfer of petroleum-related contaminants from impacted soil into edible plant tissues. These parameters provided the basis for estimating contaminant uptake into vegetables under the residential informal and subsistence exposure scenario.

3.6 Risk Assessment Approach

The human health risk assessment evaluated both carcinogenic and non-carcinogenic effects associated with exposure to petroleum-impacted surface soil. The assessment followed a risk-based approach, comparing estimated exposure with toxicological criteria to determine whether site conditions were acceptable for the selected residential receptors. This principles-based method aligns with RBCA, in which remediation and close-out decisions are based on the relationship among contaminant source concentrations, exposure pathways, receptors, and acceptable risk levels [8].

Carcinogenic risk was evaluated as the lifetime excess cancer risk (LTECR), representing the estimated probability that an individual will develop cancer over a lifetime as a result of exposure to site-related contaminants [34, 36]. For carcinogenic chemicals, we combined exposure through each complete pathway with relevant cancer toxicity values to estimate pathway-specific and total cancer risk [27]. In this study, the acceptable carcinogenic risk criterion was defined as:

$$\mathrm{ELTCR} = \sum \mathrm{Risk_{ij}} \leq 1.0 \times 10^{-6} \qquad (1)$$

This target risk level represents one additional cancer case in one million exposed individuals and is commonly used as a conservative benchmark in human health risk assessment [33, 34]. Where calculated carcinogenic risk exceeds 1.0×10^{-6}, the exposure scenario is considered to require further evaluation, remediation or risk management.

Non-carcinogenic risk was evaluated using the hazard quotient (HQ) and hazard index (HI). The hazard quotient compares the estimated exposure dose for a contaminant with its reference dose or acceptable toxicity threshold, while the hazard index sums hazard quotients across relevant chemicals and pathways [34, 36]. In this study, the acceptable non-carcinogenic criterion was defined as:

$$\mathrm{HQ} = \frac{\text{Exposure dose}}{\text{Reference dose}};\ \mathrm{HI} = \sum \mathrm{HQ_{ij}} \leq 1.0 \qquad (2)$$

A hazard index of 1 or less indicates that cumulative non-carcinogenic effects are unlikely under the modelled exposure assumptions. Conversely, HI > 1 suggests that cumulative exposure may exceed acceptable health-protective levels [34].

Accordingly, these criteria were applied to determine whether the modelled residential exposure scenario met acceptable human health risk levels.

3.7 SSTL Derivation

SSTLs were derived for the soil source to determine contaminant concentrations protective of the selected residential receptors and the complete exposure pathways identified in the CSM. Unlike generic clean-up values, SSTLs are calculated using site-specific source characteristics, contaminant composition, receptor assumptions, exposure pathways and acceptable risk criteria [6, 8].

For petroleum-impacted surface soil, the SSTL calculation considered the cumulative contribution of carcinogenic and non-carcinogenic contaminants. This was necessary because petroleum-contaminated soil contains multiple PAHs, VOCs, and TPH fractions that may collectively contribute to total risk and hazard. The calculated SSTLs therefore represent soil concentrations at which the combined risk from relevant chemicals and pathways would remain within the acceptable criteria defined in Section 3.6 [6, 8].

The original source concentration refers to the measured concentration of each contaminant or TPH fraction in the soil source, expressed in mg/kg. This represents the starting condition of the contaminated soil before risk-based adjustment. The TPH concentration represents the total petroleum hydrocarbon concentration associated with the soil source and provides the overall hydrocarbon mass used in the model. The original TPH concentration used for the study site was approximately 3900 mg/kg and was treated as the representative model-input concentration for the Tier 2 assessment.

The mass fraction describes the proportion, by mass, of each chemical or hydrocarbon fraction within the total petroleum hydrocarbon mixture [14]. It was calculated as:

$$\text{Mass fraction}_i = \frac{C_i}{TPH_{total}} \qquad (3)$$

Where C_i is the chemical concentration, and TPH_{total} is the total petroleum hydrocarbon. This parameter matters because petroleum hydrocarbons behave as

mixtures, and the relative abundance of each fraction influences toxicity, solubility, mobility, and exposure potential [18, 30].

Effective solubility represents the estimated equilibrium dissolved concentration of a chemical in water in contact with a petroleum mixture. Under ideal-mixture assumptions, it reflects both the chemical's pure-component solubility and its mole fraction in the hydrocarbon source [11, 25]. It influences contaminant release into water, subsequent transport and potential [11]. Aqueous availability also influences plant uptake, along with chemical hydrophobicity, soil properties, and plant characteristics [43].

The term TPH at SSTL refers to the total TPH concentration corresponding to the calculated site-specific target condition. It represents the reduced hydrocarbon source strength required to satisfy the risk-based criteria. The SSTLs therefore provide contaminant-specific and mixture-based targets for evaluating whether the site is suitable for certification and close-out.

3.8 Data Comparison and Certification Decision Logic

Measured residual concentrations in surface soil were compared with the calculated SSTLs to determine whether the soil source met the risk-based criteria for certification and close-out. The comparison was undertaken on a contaminant-by-contaminant basis for PAHs, VOCs/BTEX, MTBE, and the aliphatic and aromatic TPH fractions. This methodology aligns with RBCA, which involves comparing site conditions against protective concentration thresholds established to safeguard human health and the environment within specific exposure scenarios [8]. The decision rule applied in the assessment was:

$$\textit{Measured Concentration} \leq \textit{SSTL} = \textit{Compliance}$$

$$\textit{Measured Concentration} > \textit{SSTL} = \textit{Exceedance}$$

Where a measured concentration exceeded its SSTL, the result was interpreted as requiring further remediation, exposure pathway control, land-use restriction or refinement of the conceptual site model. Certification and close-out were considered supportable only where residual concentrations were below the calculated SSTLs and where relevant exposure pathways were either incomplete or adequately controlled.

Laboratory reporting limits were considered in the certification decision. For verification sampling based on non-detect results, analytical reporting limits must be at or below the relevant SSTLs. If a reporting limit exceeds the SSTL, a non-detect result cannot independently confirm that the residual concentration meets the target and should therefore be treated as inconclusive rather than compliant [4].

This ensures that close-out decisions are based on defensible evidence rather than on non-detect results that may still exceed the risk-based target concentration [4]. This practice aligns with human health risk assessment, in which risk characterisation should integrate exposure estimates, toxicity values, uncertainty, and the adequacy of supporting data [32].

3.9 Risk Modelling Software

The Tier 2 human health risk assessment and SSTL derivation were carried out using Risk Integrated Software for Cleanups Version 5 (RISC5; version 1.06.001.30EN). RISC5 was used to model petroleum-related contaminants in surface soil and to generate risk-based outputs for the selected residential exposure scenario. Input parameters included measured contaminant concentrations, petroleum hydrocarbon fractions, receptor assumptions, and exposure pathways defined in the preceding sections. Toxicity values, exposure parameters, and soil-to-plant uptake assumptions were applied within the RISC5 modelling framework, using default model values when site-specific values were unavailable. The model outputs provided the basis for estimating carcinogenic risk, non-carcinogenic hazard, SSTLs and the certification decision logic applied in this study.

3.10 Screening-Level Sensitivity and Uncertainty Analysis

A screening-level sensitivity and uncertainty analysis was undertaken to evaluate how selected model assumptions could influence the Tier 2 risk characterisation. The deterministic RISC5 model was retained as the baseline case, and selected exposure, source-term and pathway assumptions were varied around the values used in the main assessment. The purpose of this analysis was not to replace the Tier 2 SSTL calculation, but to examine whether the risk-based conclusions were sensitive to plausible changes in key input assumptions.

The parameters varied were body weight, soil ingestion rate, vegetable ingestion rate, fraction of vegetables grown in contaminated soil, exposure frequency, exposure duration, soil-source concentration and the inclusion of the plant-uptake pathway. These parameters were selected because they directly influence receptor exposure estimates, source-term assumptions and pathway-specific intake under the residential informal and subsistence exposure scenario. Particular attention was given to vegetable ingestion and plant uptake assumptions because the CSM identified the soil–plant–human pathway as a complete and potentially important exposure linkage for the study area.

The baseline values were the deterministic RISC5 model inputs used in the main assessment. We then assigned lower and higher values to selected parameters to represent plausible variation around the baseline exposure and source-term assumptions, as summarised in Table 4. We used these values as screening-sensitivity scenarios rather than as formal population percentiles. Body-weight scenarios were selected to bracket the Nigerian body-weight values used in the baseline exposure assessment, while soil ingestion, vegetable ingestion and exposure-duration scenarios were informed by exposure-factor guidance and RISC5 model-default assumptions [3, 20, 24, 29, 37, 38, 39].

For variables tested using discrete scenarios, the deterministic RISC5 value was retained as the baseline comparator. We evaluated the fraction of vegetables grown in contaminated soil at 0, 0.10, 0.25, and 0.50, where 0.25 represented the baseline model assumption. We evaluated exposure frequency at 250, 300, and 350 days/year, with 350 days/year representing the baseline deterministic input. These scenarios allowed direct comparison of lower- and higher-exposure assumptions with the main RISC5 model.

We evaluated the influence of the plant-uptake pathway by varying the fraction of vegetables grown in contaminated soils to assess the impact of soil-to-plant transfer on total carcinogenic risk and non-carcinogenic hazard.

The sensitivity analysis focused on changes in total carcinogenic risk and non-carcinogenic hazard index for the selected residential receptors. Outputs were summarised by comparing the baseline deterministic result with alternative scenario results and by identifying the assumptions that produced the greatest change in risk

and hazard. The analysis determined whether the certification and close-out interpretation remained stable under plausible alternative exposure and pathway assumptions.

Table 4 Parameters considered in the screening-level sensitivity and uncertainty analysis

Parameter	Low/reduced scenario	Baseline deterministic value	High/conservative scenario	Basis
Child body weight	13 kg	17.2 kg	22 kg	Screening range bracketing the baseline child body-weight value
Adult body weight	55 kg	64 kg	75 kg	Screening range bracketing the baseline adult body-weight value
Child soil ingestion rate	100 mg/day	200 mg/day	400 mg/day	Exposure-factor sensitivity range around RISC5 baseline input
Adult soil ingestion rate	50 mg/day	100 mg/day	200 mg/day	Exposure-factor sensitivity range around RISC5 baseline input
Child above-ground vegetable ingestion rate	27.9 g/day	55.8 g/day	83.7 g/day	0.5 ×, 1.0 × and 1.5 × baseline intake
Child root vegetable ingestion rate	24.3 g/day	48.5 g/day	72.8 g/day	0.5 ×, 1.0 × and 1.5 × baseline intake
Adult above-ground vegetable ingestion rate	63.5 g/day	127 g/day	190.5 g/day	0.5 ×, 1.0 × and 1.5 × baseline intake
Adult root vegetable ingestion rate	43.8 g/day	87.5 g/day	131.3 g/day	0.5 ×, 1.0 × and 1.5 × baseline intake
Fraction of vegetables grown in contaminated soil	0 and 0.10	0.25	0.50	Discrete land-use/pathway scenarios
Exposure frequency	250 days/year	350 days/year	300 days/year used as intermediate scenario	Discrete exposure-frequency scenarios; 350 days/year retained as baseline upper estimate
Child exposure duration	3 years	6 years	10 years	Residential exposure-duration sensitivity scenario
Adult exposure duration	30 years	45 years	60 years	Residential exposure-duration sensitivity scenario

***Note**: Baseline values are the deterministic RISC5 inputs used in the main assessment. Low/reduced and high/conservative values were used only as screening-level sensitivity scenarios; they should not be interpreted as formal population percentiles.*

Parameters that produced the largest changes in carcinogenic risk or non-carcinogenic hazard were considered the most influential assumptions for the certification decision. This provided an additional basis for evaluating whether further remediation, pathway control, land-use restriction or refinement of the conceptual site model may be needed before close-out could be supported.

4.0 Results

4.1 Carcinogenic Risk Results

The carcinogenic risk assessment produced total risks of 3.4×10^{-6} for the Child Resident – Upper Percentile receptor and 1.2×10^{-5} for the Adult Resident – Upper Percentile receptor. When the child and adult risks were combined, the cumulative residential carcinogenic risk was 1.5×10^{-5}. All three estimates exceeded the target carcinogenic risk level of 1.0×10^{-6} applied in this study.

The pathway-specific results showed that vegetable ingestion was the dominant contributor to carcinogenic risk for all receptor scenarios (Fig. 3). Vegetable ingestion accounted for approximately 85.3% of the total risk for the child receptor, 94.7% for the adult receptor, and 92.7% for the combined residential receptor. Soil ingestion contributed approximately 11.5%, 3.5%, and 5.3%, respectively, while dermal contact with soil contributed approximately 3.2%, 1.7%, and 2.1%, respectively. Inhalation of outdoor air contributed negligibly to the total carcinogenic risk.

Fig. 4 presents the chemical-specific contributions. Benzo(a)pyrene and dibenz(a,h)anthracene were the principal carcinogenic risk contributors. For the child receptor, their respective risks were 1.5×10^{-6} and 1.4×10^{-6}, increasing to 5.1×10^{-6} and 4.8×10^{-6} for the adult receptor. Their contributions to the combined residential receptor were 6.5×10^{-6} and 6.3×10^{-6}, respectively. Smaller contributions were associated with benz(a)anthracene, benzo(b)fluoranthene and indeno(1,2,3-cd)pyrene, whereas ethylbenzene, benzene, MTBE and naphthalene contributed comparatively little to the overall carcinogenic risk. Overall, the results show that PAHs and the vegetable-ingestion pathway dominated the carcinogenic risk profile, as detailed in **Supplementary Data S1**

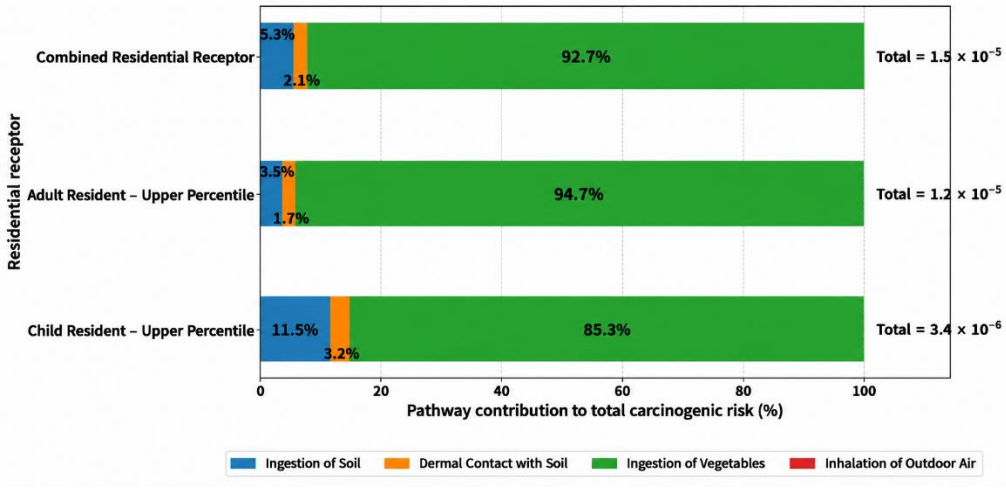


Fig. 3 Pathway contribution to carcinogenic risk

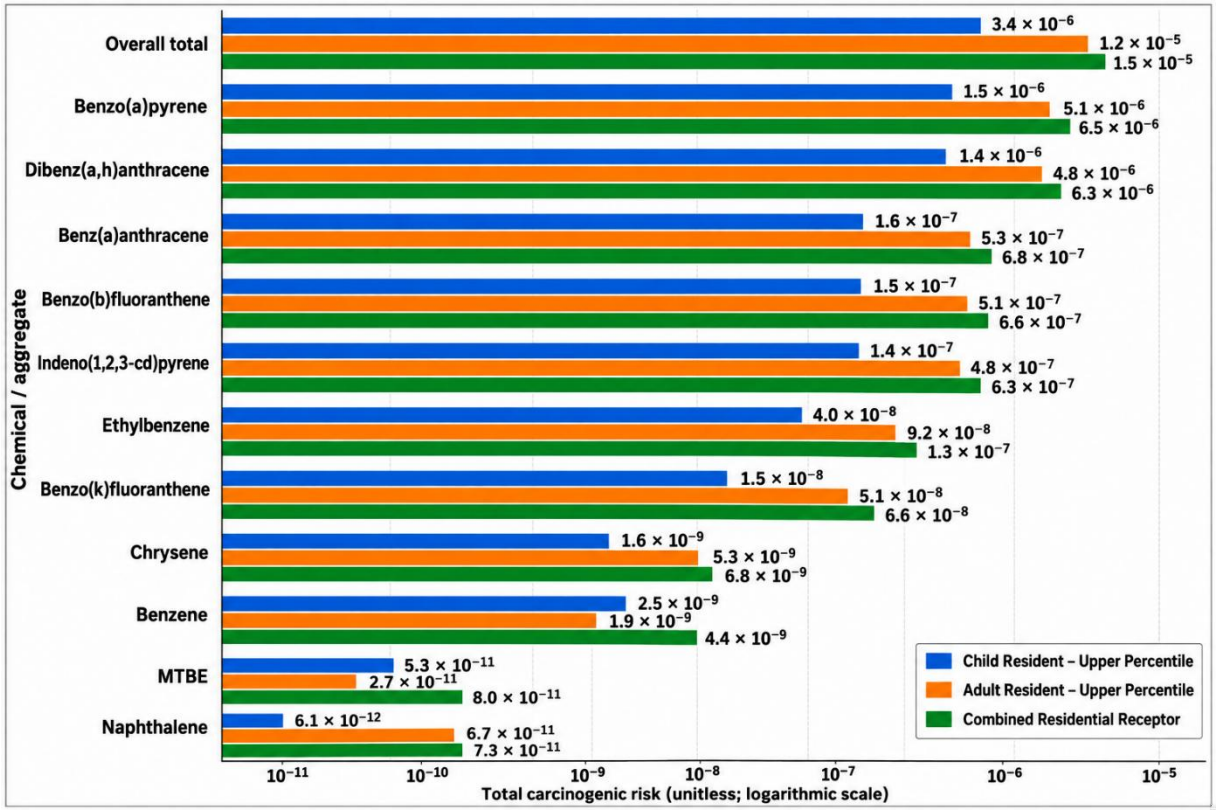


Fig. 4 Carcinogenic risk by Chemical

4.2 Non-Carcinogenic Hazard Results

The non-carcinogenic assessment produced total hazard values of 3.3×10^{1} for the Child Resident – Upper Percentile receptor and 1.5×10^{1} for the Adult Resident – Upper Percentile receptor. Both values exceeded the reference level of 1, with the child receptor showing the higher overall non-carcinogenic hazard.

The pathway-specific results showed that vegetable ingestion was the dominant exposure pathway for both receptors, as shown in Fig. 5. Vegetable ingestion contributed approximately 93.1% of the total hazard for the child receptor and 97.1% for the adult receptor. For the child receptor, dermal contact with soil contributed approximately 4.8%, while soil ingestion contributed approximately 2.1%. Corresponding contributions for the adult receptor were approximately 2.3% for dermal contact and 0.62% for soil ingestion. Inhalation of outdoor air contributed negligibly to the total non-carcinogenic hazard for both receptors.

Fig. 6 presents the chemical-specific contributions. The heavier aromatic TPH fractions dominated the non-carcinogenic hazard, particularly TPH Aromatic C21–35 and TPH Aromatic C16–21. TPH Aromatic C21–35 contributed hazard quotients of approximately 27 for the child receptor and 13 for the adult receptor, while TPH Aromatic C16–21 contributed approximately 4.6 and 2.1, respectively. TPH Aromatic C12–16 also contributed to the overall hazard, with values of approximately 1.2 for the child receptor and 0.50 for the adult receptor. The remaining TPH fractions and individual compounds contributed substantially lower hazard quotients.

Overall, the results show that vegetable ingestion and the heavier aromatic TPH fractions drove the non-carcinogenic hazard profile, with TPH Aromatic C21–35 as the largest individual contributor for both residential receptors.

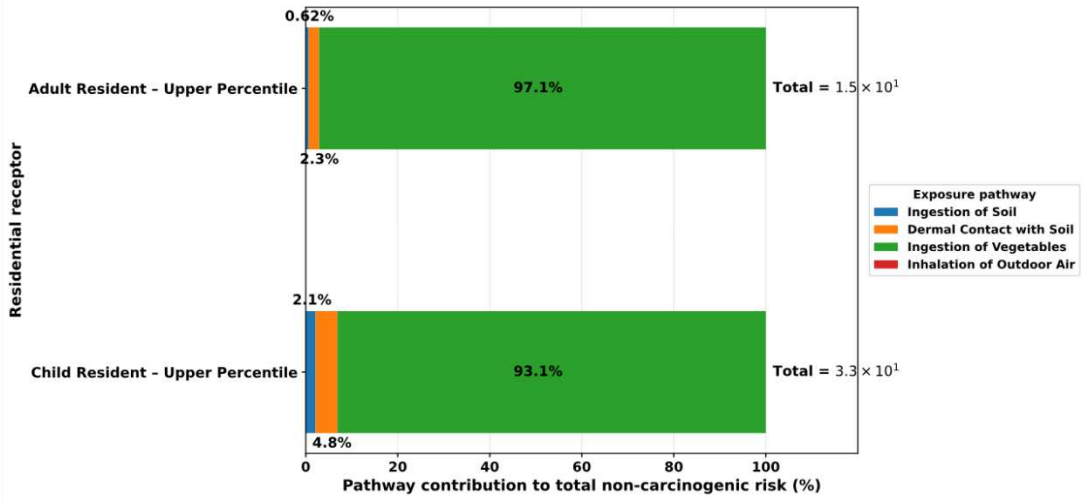


Fig. 5 Pathway contribution to Non-carcinogenic hazard

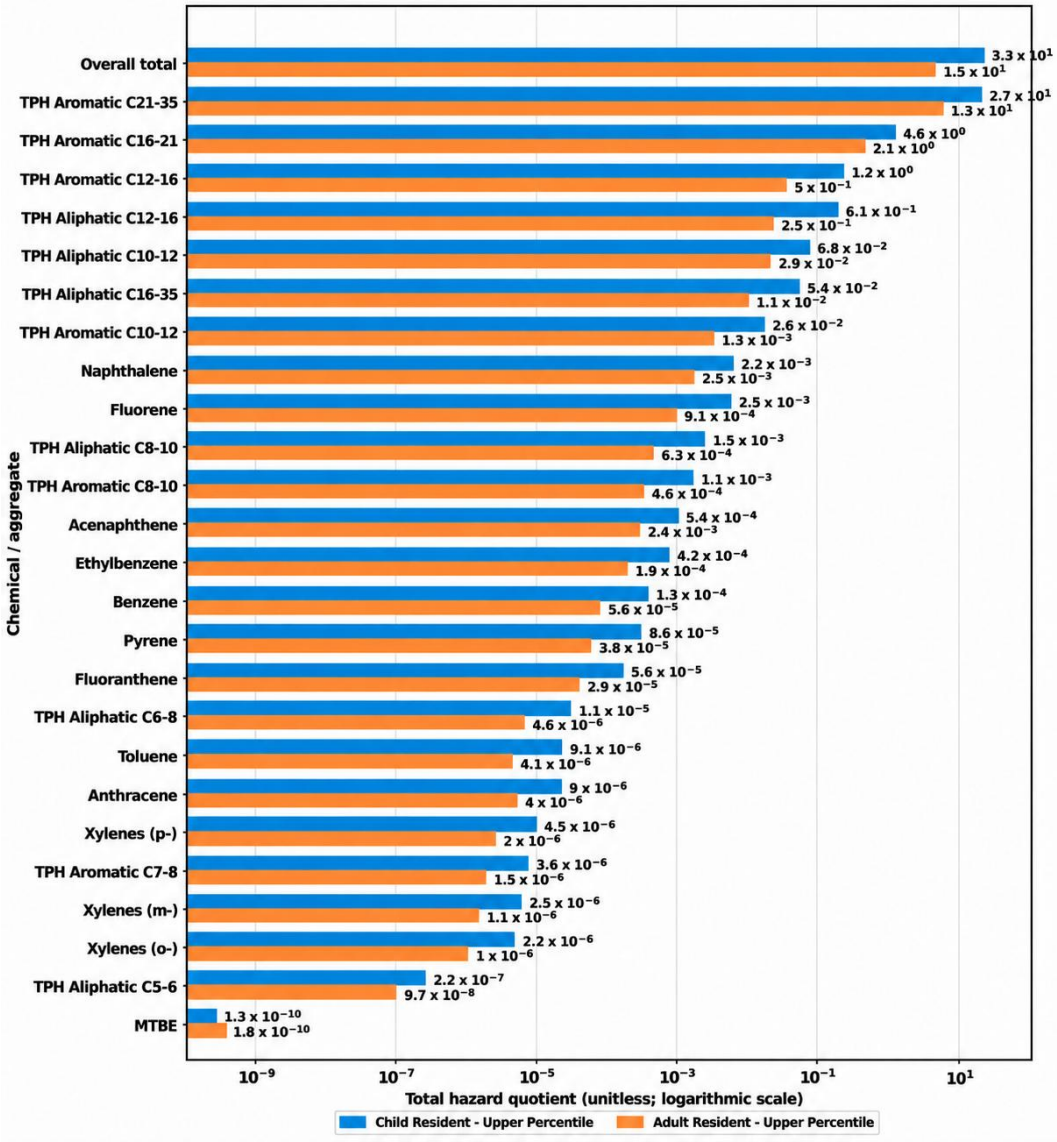


Fig 6. Non-carcinogenic hazard by chemical

4.3 Original Soil Source Condition

The original soil source condition represents the measured contaminant concentrations used as inputs for the Tier 2 risk assessment and SSTL derivation. The soil source was characterised by petroleum hydrocarbon fractions, PAHs and VOCs/BTEX compounds, with a total petroleum hydrocarbon concentration of approximately 3.9×10^3 mg/kg.

The hydrocarbon profile was dominated by medium- to high-carbon-number TPH fractions, consistent with a weathered petroleum source [14]. This pattern suggests that lighter components may have been depleted through volatilisation, dissolution and biodegradation [11]. The persistence of heavier fractions may reflect their lower volatility and limited bioavailability, with sorption to soil and compound-specific resistance to biodegradation contributing to slower removal [14, 23].

The largest fraction was TPH Aliphatic C16–35, with an original concentration of approximately 1500 mg/kg, accounting for about 38% of the total TPH mass. This was followed by TPH Aromatic C21–35 at approximately 1100 mg/kg, representing about 28% of the total TPH. Other important contributors were TPH Aliphatic C12–16 at approximately 520 mg/kg, TPH Aromatic C16–21 at approximately 480 mg/kg, and TPH Aromatic C12–16 at approximately 260 mg/kg, as shown in Fig. 7.

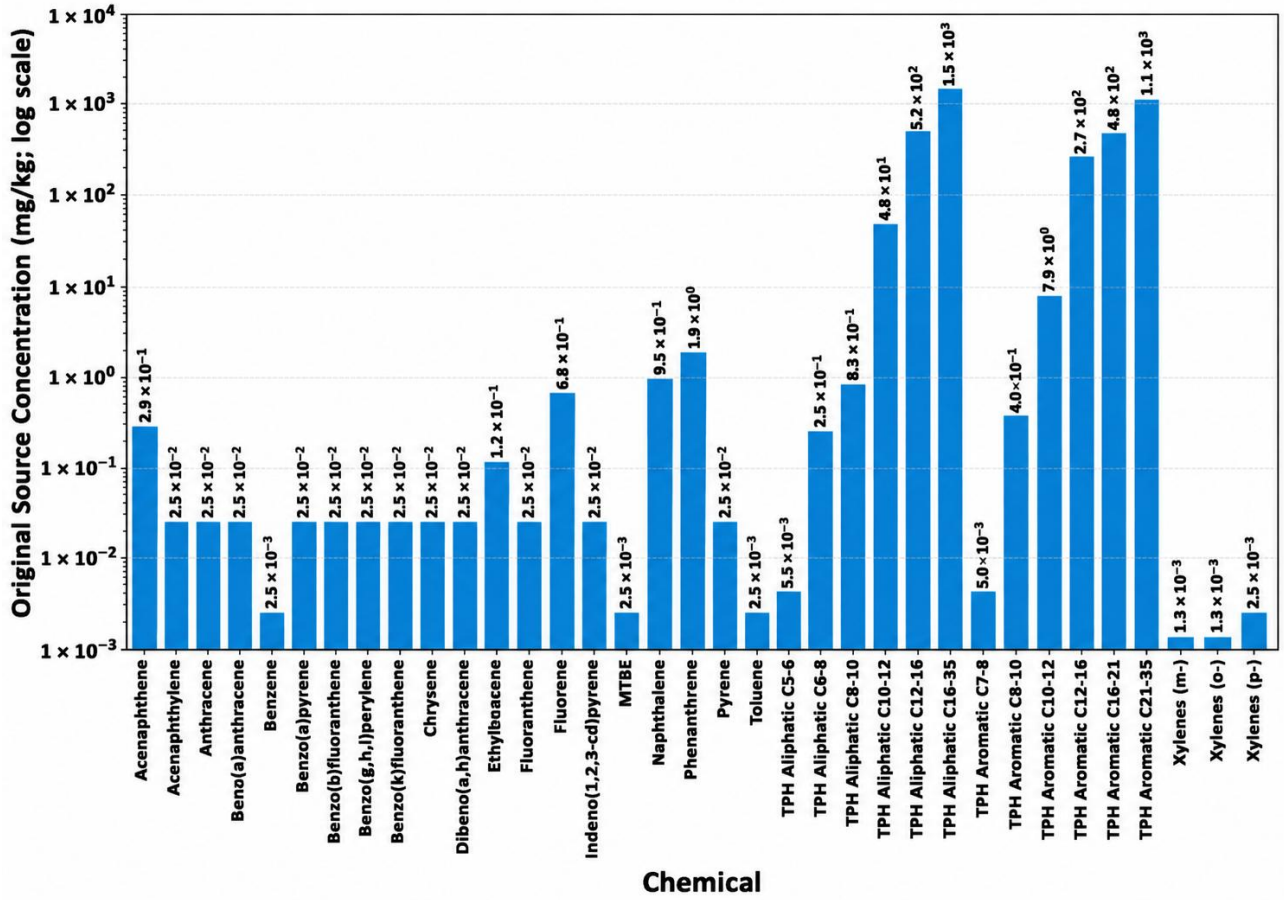


Fig. 7 Original source composition: Original source composition by chemical and TPH fractions

4.4 SSTL Results

The calculated SSTLs were substantially lower than the original soil-source concentrations for the contaminants and TPH fractions evaluated under the selected residential exposure scenario. The original total petroleum hydrocarbon concentration was approximately 3.9 × 10³ mg/kg, whereas the corresponding modelled TPH concentration at SSTL was 1.1 × 10² mg/kg (110 mg/kg). This represents an approximate reduction of 97% relative to the original TPH source concentration:

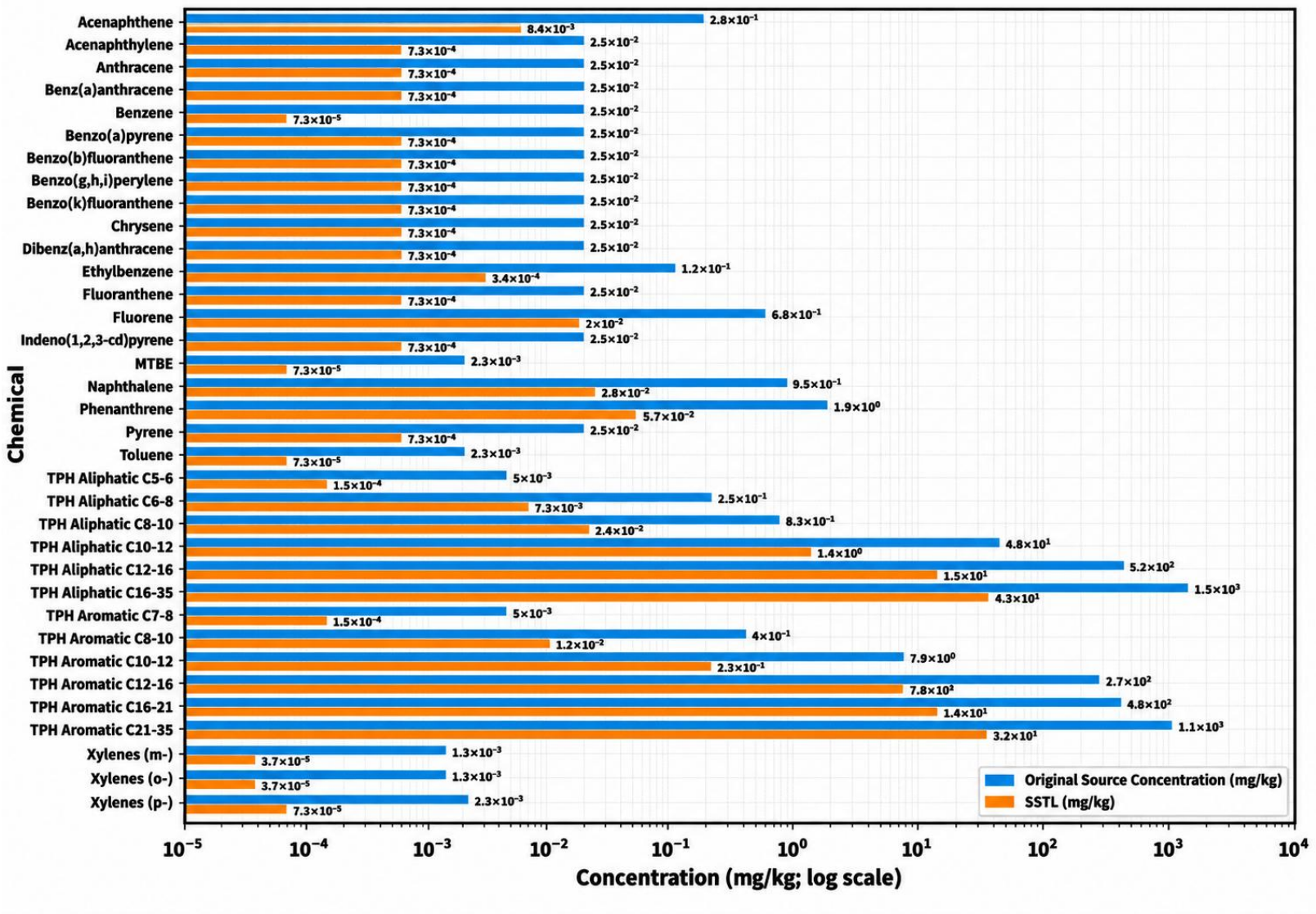
$$\text{Required reduction (\%)} = \frac{3900 - 110}{3900} \times 100 \approx 97\% \qquad (4)$$

Fig. 8 compares the original source concentrations with the individual SSTLs. The largest original TPH fractions considerably exceeded their corresponding SSTLs. TPH Aliphatic C16–35 decreased from 1.5 × 10³ mg/kg to an SSTL of 4.3 × 10¹ mg/kg, while TPH Aromatic C21–35 decreased from 1.1 × 10³ mg/kg to 3.2 × 10¹ mg/kg. Similarly,

TPH Aliphatic C12–16 had an original concentration of 5.2×10^{2} mg/kg compared with an SSTL of 1.5×10^{1} mg/kg, and TPH Aromatic C16–21 decreased from 4.8×10^{2} mg/kg to 1.4×10^{1} mg/kg. TPH Aromatic C12–16 also exceeded its SSTL, with an original concentration of 2.6×10^{2} mg/kg compared with a target level of 7.8 mg/kg.

Exceedances were also observed for the lighter TPH fractions and individual compounds. For example, TPH Aromatic C8–10 had an original concentration of 4.0 $\times 10^{-1}$ mg/kg compared with an SSTL of 1.2×10^{-2} mg/kg, while benzene decreased from 2.5×10^{-3} mg/kg to an SSTL of 7.3×10^{-5} mg/kg. The original concentrations of m- and o-xylene were 1.3×10^{-3} mg/kg, compared with SSTLs of 3.7×10^{-5} mg/kg, whereas p-xylene decreased from 2.5×10^{-3} mg/kg to 7.3×10^{-5} mg/kg. PAHs also showed marked differences between the original concentrations and calculated SSTLs; for example, benzo(a)pyrene and dibenz(a,h)anthracene each had original concentrations of 2.5×10^{-2} mg/kg, compared with SSTLs of 7.3×10^{-4} mg/kg.

Overall, the results show that the original source concentrations exceeded the calculated SSTLs across the evaluated contaminants and TPH fractions. The individual SSTLs therefore provide contaminant- and fraction-specific target concentrations alongside the overall TPH concentration at SSTL, allowing quantification of the difference between the original soil-source condition and the modelled risk-based target condition.



683

684 **Fig. 8** Original source concentration versus SSTL for soil source

4.5 Sensitivity and Uncertainty Results

The screening-level sensitivity analysis showed that the vegetable-ingestion pathway, the fraction of vegetables assumed to be grown in contaminated soil, and the vegetable ingestion rate most strongly influenced the overall risk conclusion. Parameters affecting direct soil contact, such as soil ingestion rate and dermal exposure assumptions, had a smaller influence on the total risk outcome.

When the vegetable-ingestion pathway was retained, carcinogenic risk and non-carcinogenic hazard generally remained above the adopted acceptability criteria. In contrast, reducing or excluding the vegetable-ingestion pathway substantially reduced the estimated risk and hazard, confirming that land-use assumptions and plant-uptake exposure are critical to the certification decision.

The detailed sensitivity model outputs are provided as Supplementary Data P3–P12. These supplementary files include SSTL and risk-result outputs for the high, reduced, baseline and excluded vegetable-ingestion scenarios, based on changes to the fraction of vegetables grown in contaminated soil (FoVGICS). They also include separate outputs for scenarios in which the plant-uptake model was excluded from the RISC5 calculation. Together, these outputs provide supporting evidence for identifying the exposure assumptions that most strongly influenced the certification and close-out interpretation.

These findings indicate that the deterministic RISC5 results are conservative but are not arbitrary; they are primarily controlled by clearly identifiable exposure assumptions. The sensitivity analysis therefore supports the conclusion that unrestricted residential close-out would require either further reduction of residual contamination, defensible evidence that vegetable cultivation and consumption are not realistic exposure pathways, or enforceable land-use/pathway controls.

5. Discussion

5.1 Implication of Risk Exceedance for Certification

For the study area, the risk assessment results have direct implications for certification and site close-out under the modelled residential exposure scenario. Both carcinogenic risk and non-carcinogenic hazard exceeded the adopted acceptability criteria. The estimated carcinogenic risks were 3.4×10^{-6} for the Child Resident –

Upper Percentile receptor, 1.2×10^{-5} for the Adult Resident – Upper Percentile receptor, and 1.5×10^{-5} for the combined residential receptor. The corresponding non-carcinogenic hazard indices were approximately 33 for the child receptor and 15 for the adult receptor. These values exceeded the adopted criteria of ELTCR ≤ 1.0×10^{-6} and HI ≤ 1.0, indicating that the modelled residential exposure condition did not satisfy the risk-based acceptability criteria applied in this study.

From a certification perspective, these findings indicate that the current soil-source condition would not support unrestricted residential close-out under the modelled exposure assumptions. Close-out may require further evidence that residual contaminant concentrations have been reduced to acceptable site-specific levels, that relevant exposure pathways are demonstrably incomplete or effectively controlled, or that the CSM can be defensibly refined using additional site-specific evidence. This interpretation is consistent with RBCA principles, in which risk-management and close-out decisions are based on the relationship between contaminant sources, exposure pathways and receptors under defined land-use conditions [8].

5.2 Importance of the Vegetable Ingestion Pathway

Vegetable ingestion was the dominant exposure pathway for both carcinogenic risk and non-carcinogenic hazard under the modelled residential scenario. For carcinogenic risk, vegetable ingestion contributed approximately 2.9×10^{-6} for the Child Resident – Upper Percentile receptor, 1.1×10^{-5} for the Adult Resident – Upper Percentile receptor, and 1.4×10^{-5} for the combined residential receptor. These contributions represented approximately 85.3%, 94.7% and 92.7% of the respective total carcinogenic risks. For non-carcinogenic hazard, vegetable ingestion contributed approximately 31 for the child receptor and 15 for the adult receptor, corresponding to approximately 93.1% and 97.1% of the respective total hazard. The pathway-specific values alone exceeded the adopted criteria of ELTCR ≤ 1.0×10^{-6} and HI ≤ 1.0, indicating that vegetable ingestion was a major determinant of the modelled risk outcome and derived SSTLs.

This finding illustrates how land-use assumptions can directly influence the risk assessment underpinning certification decisions [15]. In residential or informal subsistence settings where vegetables are grown and consumed locally, contaminated produce may create an additional exposure pathway alongside incidental soil ingestion

and dermal contact. Exposure assessment guidance recognises ingestion, dermal absorption and inhalation as the principal exposure routes. Food consumption should therefore be considered where contaminants can transfer from soil or water into locally consumed produce [39].

For the study area, vegetable ingestion could remain in the CSM where cultivation is occurring, likely to occur, or cannot be reliably prevented under future residential use [8, 15]. Excluding this pathway without site-specific evidence may underestimate both carcinogenic and non-carcinogenic risks. However, the pathway may be refined or excluded if land-use records, field observations, community land-use information, physical barriers, institutional controls, or enforceable future-use restrictions support it [15]. This distinction is important because the defensibility of certification depends on whether the exposure assumptions reflect realistic site use.

5.3 Difference Between Cancer and Non-Cancer Risk Drivers

The contrast between carcinogenic and non-carcinogenic risk drivers is important for interpreting the site assessment results. PAHs, particularly benzo(a)pyrene and dibenz(a,h)anthracene, dominated carcinogenic risk. For the combined residential receptor, these compounds contributed approximately 6.5×10^{-6} and 6.3×10^{-6}, respectively, and together accounted for most of the total combined carcinogenic risk of 1.5×10^{-5}. Other PAHs, including benz(a)anthracene, benzo(b)fluoranthene and indeno(1,2,3-cd)pyrene, contributed to the cumulative carcinogenic risk to a lesser extent, with combined contributions of approximately 6.8×10^{-7}, 6.6×10^{-7} and 6.3×10^{-7}, respectively.

In contrast, the heavier aromatic TPH fractions, rather than individual PAHs or BTEX compounds, controlled the non-carcinogenic hazard. The principal non-cancer hazard driver was TPH Aromatic C21–35, with hazard quotients of approximately 27 for the child receptor and 13 for the adult receptor. TPH Aromatic C16–21 was the next largest contributor, with values of approximately 4.6 and 2.1, respectively. TPH Aromatic C12–16 also contributed, with hazard quotients of approximately 1.2 for the child receptor and 0.50 for the adult receptor. These findings highlight the value of fraction-specific TPH assessment, as bulk TPH concentration alone does not distinguish the hydrocarbon fractions that contribute most to non-carcinogenic hazard [18, 31].

This distinction has practical implications for remediation and verification. Reduction in total TPH concentration alone may not adequately address the risk profile if individual PAH-related carcinogenic drivers remain above their SSTLs [18]. Similarly, low concentrations of BTEX compounds do not, by themselves, indicate acceptable risk where heavier aromatic TPH fractions continue to contribute substantially to non-carcinogenic hazard [26]. These findings indicate that risk-based close-out should verify both PAH-related carcinogenic drivers and heavier aromatic TPH hazard drivers against their relevant site-specific target levels [8].

5.4 Analytical Reporting Limit Limitation

An important limitation of the SSTL results is that several calculated target levels are very low and may approach or fall below achievable laboratory reporting limits. This has implications for verification sampling because compliance can only be demonstrated where the analytical method provides sufficient sensitivity to distinguish concentrations below the relevant SSTLs. Where the laboratory reporting limit exceeds the SSTL, a non-detect result does not necessarily demonstrate that the contaminant concentration is below the risk-based target [14, 19].

This issue is evident in the SSTL outputs for the study area. The calculated SSTLs for benzene and MTBE were 7.3×10^{-5} mg/kg, while the SSTLs for m- and o-xylene were 3.7×10^{-5} mg/kg and that for p-xylene was 7.3×10^{-5} mg/kg. Several PAHs, including benzo(a)pyrene, benz(a)anthracene, chrysene, benzo(b)fluoranthene and dibenz(a,h)anthracene, had SSTLs of approximately 7.3×10^{-4} mg/kg. These comparatively low target concentrations indicate that analytical sensitivity may become an important consideration when evaluating compliance with the derived SSTLs.

For example, where the benzene SSTL is 7.3×10^{-5} mg/kg and the applicable laboratory reporting limit is 5.0×10^{-3} mg/kg, a non-detect result reported as $< 5.0 \times 10^{-3}$ mg/kg would not, by itself, demonstrate compliance because the reporting limit would remain approximately 34 times higher than the SSTL. A similar limitation applies to PAHs, where the derived SSTLs are approximately 7.3×10^{-4} mg/kg, but the applicable analytical reporting limits exceed these concentrations.

Accordingly, analytical reporting limits represent an important source of uncertainty in post-remediation verification [19]. Where available analytical methods cannot achieve

reporting limits equal to or below the derived SSTLs, this limitation may need to be acknowledged when interpreting verification results [4]. Considering analytical sensitivity alongside risk drivers, exposure pathway controls, and residual contaminant concentrations may therefore provide a more robust basis for evaluating whether the intended land-use condition has been achieved [15].

5.5 Uncertainty and Limitations

This assessment is subject to uncertainties associated with plant uptake modelling, exposure assumptions, data representativeness and future land use. The vegetable ingestion pathway had a controlling influence on the SSTLs; therefore, the validity of the outcome depends on whether cultivation and consumption of locally grown produce are realistic for the study area. Additional field evidence on current and future agricultural and gardening practices may strengthen the CSM and improve the defensibility of any close-out decision.

A further limitation is that the available laboratory certificate reported analytical methods, accreditation status and numerical detection limits, but did not include the full laboratory QA/QC package, such as matrix-matched CRM recovery percentages, surrogate recoveries, matrix-spike recoveries, blanks or duplicate precision. The results are therefore suitable for risk-based interpretation of the available secondary dataset, but future verification should include full analytical QA/QC documentation to support regulatory close-out decisions.

Model assumptions also influence the derived risk estimates. Where RISC5 default values were used, the results were interpreted with awareness of uncertainty in toxicity values, exposure parameters, soil-to-plant transfer, contaminant bioavailability, and soil transport parameters. The original TPH concentration used in the model was approximately 3892 mg/kg, rounded to 3900 mg/kg, and was derived from 95% upper confidence limit concentrations calculated using USEPA ProUCL software version 5.1. Therefore, the uncertainty is not related to whether the value represents a maximum, mean or 95% UCL, but rather to whether the underlying dataset adequately captures spatial variability and the representative source condition for the site.

Using 95% UCL values provides a conservative and defensible basis for estimating exposure from the soil source. However, the reliability of this input still depends on the number, distribution and quality of the samples used to calculate the UCLs. These

uncertainties should therefore be acknowledged when interpreting the findings and when applying them to certification and close-out decisions.

5.6 Relevance to Nigerian Contaminated Land Management

The findings from this study are relevant to contaminated land management in Nigeria because they demonstrate how site-specific exposure conditions can influence close-out decisions. Hydrocarbon-contaminated sites in the Niger Delta are often assessed using fixed generic TPH-based clean-up values, but these values may not fully account for land use, receptor sensitivity, contaminant fractionation, cumulative risk or complete exposure pathways. In Ogoniland, where hydrocarbon contamination has raised long-standing concerns about soil and water quality, ecosystem health and local livelihoods, a site-specific risk-based approach provides a more defensible basis for evaluating remediation endpoints and future land reuse [40].

The results show that a site may appear close to acceptability under a fixed generic TPH-based approach but still fail a site-specific human health risk assessment when realistic residential and subsistence exposure pathways are included. In this assessment, the outcome was driven by interactions among contaminant composition, exposure pathway completeness, and receptor assumptions, not total hydrocarbon mass alone. These findings illustrate the potential value of risk-based certification approaches that explicitly evaluate source–pathway–receptor linkages, fractionated TPH data, PAHs, VOCs, and cumulative risk.

For Nigerian contaminated land practice, this study suggests that certification decisions may be strengthened by evidence of protectiveness, rather than reliance on fixed generic values alone. SSTLs can support this process by linking residual concentrations to defined exposure scenarios, health-protective criteria and site-specific conditions.

5.7 Policy and Regulatory Implications

The findings of this study provide evidence supporting a tiered, risk-based regulatory framework for remediation certification and close-out of hydrocarbon-contaminated sites in Nigeria. Such a framework could retain Tier 1 screening as an initial decision step, with Tier 2 assessment considered where screening values are exceeded or where sensitive land-use conditions warrant further site-specific evaluation [36].

Tier 2 assessment may include deriving SSTLs using measured site data, receptor assumptions, exposure pathways, contaminant behaviour, and acceptable risk criteria. For petroleum-contaminated sites, this assessment could include PAHs, BTEX/MTBE and fractionated TPH data rather than relying only on bulk TPH, because petroleum fractions differ in toxicity, solubility, volatility, sorption and persistence [9].

Certification could be supported by a clear CSM that identifies the contaminant source, affected media, relevant exposure pathways and receptors. Where a pathway is excluded, the basis for its exclusion should be supported by available site-specific evidence or appropriate controls. Verification could also be informed by the exposure pathways identified as contributing most substantially to risk; for example, where vegetable ingestion is an important pathway, verification may need to include root-zone soil and contaminants relevant to plant uptake.

Finally, laboratory reporting limits should be sufficiently low to enable meaningful comparison with the derived SSTLs. Where an SSTL is below the analytical reporting limit, a non-detect result does not, by itself, demonstrate compliance and may therefore be considered inconclusive. Nigerian contaminated land regulation could consequently move toward a certification system that integrates Tier 1 screening, Tier 2 SSTL derivation, CSM-based pathway evaluation, pathway-specific verification and adequate analytical sensitivity.

6.0 Conclusion

This study evaluated the suitability of a hydrocarbon-contaminated site in MOGHO, Bodo Community, Niger Delta, for risk-based certification and close-out using a Tier 2 SSTL approach under a residential informal and subsistence exposure scenario. The results show that the residual petroleum hydrocarbon source was dominated by medium- and heavy-carbon-number TPH fractions, indicating that the remaining contamination is mainly associated with persistent petroleum fractions rather than light, volatile hydrocarbons.

The human health risk assessment showed that the site does not meet the adopted residential risk criteria. Carcinogenic risk exceeded the target level of 1.0×10^{-6} for the child, adult and combined residential receptors, while non-carcinogenic hazard indices also exceeded the acceptable threshold of 1.0. PAHs mainly drove

carcinogenic risk, whereas heavier aromatic TPH fractions primarily controlled non-carcinogenic hazard.

Vegetable ingestion was the dominant exposure pathway for both risk endpoints, demonstrating that residential and subsistence land-use assumptions strongly influence the risk outcome and derived SSTLs. Where vegetable cultivation and consumption are realistic, including this pathway in the CSM may be appropriate unless site-specific evidence supports its exclusion or effective control.

The SSTL results confirm that the current soil source condition is not acceptable for unrestricted residential close-out under the modelled exposure assumptions. The calculated TPH at SSTL was approximately 110 mg/kg compared with an original TPH concentration of approximately 3,900 mg/kg, indicating that substantial contaminant reduction would be required. In addition, individual PAHs and TPH fractions exceeded their SSTLs, highlighting the value of contaminant-specific and fraction-specific assessment alongside bulk TPH in certification decisions. Further remediation, exposure pathway control, land-use restrictions, or defensible CSM refinement may therefore be necessary before close-out can be supported. Overall, the findings demonstrate case-study evidence supporting further consideration of a risk-based certification framework in Nigeria that incorporates contaminant fractionation, receptor-specific exposure assessment, cumulative risk evaluation, and verification against SSTLs.

Statements and Declaration

Funding

This research received no funding. However, it was undertaken under a fully funded scholarship by the Petroleum Technology Development Fund (PTDF), Nigeria, through its overseas scholarship program, which supports postgraduate research and human capacity development in the petroleum sector.

Competing Interests

The author (SA) is currently employed by the National Oil Spill Detection and Response Agency (NOSDRA) and is a PhD student at the University of Strathclyde in the United Kingdom. NOSDRA and the funding body had no role in the study design or manuscript preparation. The authors declare no other competing interests.

Ethics Approval

This study did not involve human participants, animals, or sensitive personal data. Therefore, formal ethical approval was not required.

Consent to Participate and Consent to Publish: Not applicable.

Ethical Responsibilities of Authors

All authors have read, understood, and complied, as applicable, with the statement on Ethical Responsibilities of Authors as found in the Instructions for Authors

Clinical trial number: Not applicable

Data Availability

The data supporting this study's findings were obtained from secondary environmental site investigation reports provided by NOSDRA. These data are not publicly available because they are subject to institutional restrictions and confidentiality agreements. Data may be made available from the corresponding author upon reasonable request and with permission from NOSDRA.

Author Contributions

S.A. conceived the study, designed the methodology, compiled and analysed the secondary environmental and hydrogeological data, interpreted the results, prepared the figures and tables, and wrote the original manuscript. C.K. contributed to the study's conceptual development, advised on the methodology and interpretation of the results, critically reviewed and revised the manuscript, and approved the final version. All authors read and approved the final manuscript.

Acknowledgments

The authors gratefully acknowledge PTDF, Nigeria, for providing financial support for the PhD programme under which this research was undertaken. The authors also thank the University of Strathclyde for providing the academic environment that supported this study. This research used secondary environmental and hydrogeological data from existing site investigation reports. The authors sincerely acknowledge the NOSDRA for providing access to these datasets. Their contributions

to environmental site characterisation, monitoring, and data management were fundamental to the analyses presented in this manuscript

Supplementary Information

Supplementary Data S1 and S2. RISC5 modelling output spreadsheet showing the input concentrations, receptor-specific risk estimates, pathway contributions and calculated SSTLs used in the Tier 2 assessment.

Supplementary Data P3–P12. Screening-level sensitivity and uncertainty analysis outputs for the RISC5 Tier 2 assessment. These files include SSTL and risk-result outputs for alternative vegetable-ingestion scenarios based on changes to the fraction of vegetables grown in contaminated soil (FoVGICS), including high, reduced, baseline and excluded pathway assumptions, as well as separate scenarios in which the plant-uptake model was excluded.

References

1. Agency for Toxic Substances and Disease Registry (ATSDR). (2021). Exposure dose guidance for determining life expectancy and exposure factor (Version 3). U.S. Department of Health and Human Services, Public Health Service. https://www.atsdr.cdc.gov/pha-guidance/resources/ATSDR-EDG-Life-Expectancy-Exposure-Factor-508.pdf

2. Agency for Toxic Substances and Disease Registry (ATSDR). (2023). Toxicological profile for methyl tert-butyl ether (MTBE). U.S. Department of Health and Human Services, Public Health Service. https://www.atsdr.cdc.gov/toxprofiles/tp91.pdf

3. Agofure, O. (2018). Prevalence of obesity among adults in Issele-Uku, Delta State Nigeria. Alexandria Journal of Medicine, 54(4), 463–468. https://doi.org/10.1016/j.ajme.2017.10.005

4. Alaska Department of Environmental Conservation. (2022). Guidelines for data reporting (Technical Memorandum 22-001). https://dec.alaska.gov/media/25979/guidelines-for-data-reporting.pdf

5. ASTM International. (2014). Standard guide for risk-based corrective action for protection of ecological resources (ASTM Standard No. E2205/E2205M-02(2014)). https://doi.org/10.1520/E2205_E2205M-02R14

6. ASTM International. (2015). Standard guide for risk-based corrective action applied at petroleum release sites (ASTM Standard No. E1739-95(2015)). https://doi.org/10.1520/E1739-95R15.

7. ASTM International. (2020). Standard guide for developing conceptual site models for contaminated sites (ASTM Standard No. E1689-20). https://doi.org/10.1520/E1689-20

8. ASTM International. (2022). Standard guide for risk-based corrective action (ASTM Standard No. E2081-22). https://doi.org/10.1520/E2081-22

9. Bai, J., Jiang, J., Yan, Z., Wang, Q., Zhang, C., Yang, P., & Yang, M. (2024). Distribution, migration, and segmented risk assessment of the total petroleum hydrocarbons in soil, groundwater, and soil gas at an oil refinery. Regional Studies in Marine Science, 77, Article 103714. https://doi.org/10.1016/j.rsma.2024.103714

10. Batbaatar, N., Fu, X., Bartelli, D., Naser, A. M., & Jia, C. (2025). Exposures to polycyclic aromatic hydrocarbons among adults and children: Contributions from multiple pathways and sources. Environmental Research, 274. https://doi.org/10.1016/j.envres.2025.121325

11. Bekins, B. A., & Herkelrath, W. N. (2026). Natural source zone depletion of crude oil in the subsurface: processes controlling mass losses of individual compounds. Water Resources Research, 62(1), e2025WR041964.

12. Beygisangchin, M., Jakmunee, J., Kamarudin, S. K., Baghdadi, A. H., Saetang, S., & Thipprasert, S. (2026). A critical review of polycyclic aromatic hydrocarbons and their adverse effects on human health: insights from the past six years. Environmental Sciences Europe 2026 38:1, 38(1), 87-. https://doi.org/10.1186/S12302-026-01367-Y

13. Department of Petroleum Resources (DPR). (2018). Environmental guidelines and standards for the petroleum industry in Nigeria (EGASPIN) (3rd ed.). Department of Petroleum Resources, Ministry of Petroleum Resources.

14. DeVaull, G. E., Bonte, M., Gundlach, E. R., & Iroakasi, O. I. (2025). Development and application of human health risk-based screening levels for crude oil-affected soils and sediments in the Niger Delta. Integrated Environmental Assessment and Management. https://doi.org/10.1093/INTEAM/VJAF052

15. Environment Agency. (2020). LCRM: Stage 3 remediation and verification. GOV.UK. https://www.gov.uk/government/publications/land-contamination-risk-management-lcrm/lcrm-stage-3-remediation-and-verification

16. Hashemi, S. H., Kaykhaii, M., Mirmoghaddam, M., & Boczkaj, G. (2021). Preconcentration and Analytical Methods for Determination of Methyl Tert-Butyl Ether and Other Fuel Oxygenates and Their Degradation Products in Environment: A Review. Critical Reviews in Analytical Chemistry, 51(6), 582–608. https://doi.org/10.1080/10408347.2020.1753164

17. Huang, Y., Chen, Y., Wu, Q., Shi, P., Yang, B., & Xie, Y. (2024). Evaluation of BTEX pollution and health risk for sustainable use of a typical chemical pesticide industrial site. Sustainability, 16(15), Article 6494. https://doi.org/10.3390/su16156494

18. Interstate Technology & Regulatory Council (ITRC). (2018). TPH risk evaluation at petroleum-contaminated sites (TPHRisk-1). Interstate Technology & Regulatory Council, TPH Risk Evaluation Team. https://tphrisk-1.itrcweb.org

19. Interstate Technology & Regulatory Council (ITRC). (2022). Analytical data quality review: Verification, validation, and usability [Fact sheet]. https://edm-1.itrcweb.org/analytical-data-quality-review/

20. Johnson, O. E., Olatunji, G. O., Akan, M. E., Ekumakpu, M. M., Nkanta, F. S., Ntuk, F. D., Adeniyi, J. O., Udoh, P. F., & Affia, G. S. (2025). Anthropometric assessment of nutritional status of under-five children attending paediatrics clinic in University of Uyo Teaching Hospital, Nigeria. The Nigerian Health Journal, 25(2), 869–878. https://doi.org/10.71637/tnhj.v25i2.1106

21. Li, H., Gu, X., Song, J., Hui, K., Chen, G., Tan, W., Wang, H., Jiang, Y., & Yuan, Y. (2024). Effects of soil-groundwater environmental factors on BTEX transport and transformation: A review. Journal of Environmental Chemical Engineering, 12(5), 113697. https://doi.org/10.1016/J.JECE.2024.113697

22. Lupu, R., Cocarta, D. M., & Verginelli, I. (2026). Evaluating human health risk assessment tools for contaminated soil: a comparative review. Environmental Science and Pollution Research, 33(7), 2445–2473. https://doi.org/10.1007/s11356-026-37411-w

23. Mekonnen, B. A., Aragaw, T. A., & Genet, M. B. (2024). Bioremediation of petroleum hydrocarbon-contaminated soil: A review on principles, degradation mechanisms, and advancements. Frontiers in Environmental Science, 12, Article 1354422. https://doi.org/10.3389/fenvs.2024.1354422

24. Okoseimiema, S. C., Bob-Manuel, I. F., & Ebhojaye, K. I. (2026). Educational level and perception of body mass index among the Ekpeye ethnic group in Rivers State, Nigeria. Asian Journal of Biology, 22(5), 76–87. https://doi.org/10.9734/ajob/2026/v22i5654.

25. Patil, P., Jeppu, G. P., Vasudevan, M., & Girish, C. R. (2023). A review on dissolution of multi-component non-aqueous phase liquids: Recent studies, mechanisms and mass transfer limitations. Desalination and Water Treatment, 283, 164–184. https://doi.org/10.5004/dwt.2023.29230

26. Rice, G. E., Phillips, A. L., & Owens, E. O. (2022). Provisional peer-reviewed toxicity values for the aromatic high carbon range total petroleum hydrocarbon (TPH) fraction (noncancer) (various CASRNs). U.S. Environmental Protection Agency. https://www.ncbi.nlm.nih.gov/books/NBK599829/

27. Scerri, M. M., Haas, K., Gauci, A., & Schiedek, T. (2026). Atmospheric deposition of polycyclic aromatic hydrocarbons in southwestern German soils: Sources, cancer risks and policy implications. Environmental Sciences Europe, 38, Article 88. https://doi.org/10.1186/s12302-026-01362-3

28. Singh, R. K., & Singh, S. K. (2025). Persistent polycyclic aromatic hydrocarbons (PAHs) in the soil, its bioremediation, and health effects. Environmental Sciences Europe, 37(1), 187. https://doi.org/10.1186/s12302-025-01230-6

29. Spence, L., & Walden, T. (2011). RISC5 user's guide. https://manuals.plus/m/aaf282ab665609481634f28528f31a556bceb70de0161826e84dc466eaadde10.pdf

30. Total Petroleum Hydrocarbon Criteria Working Group. (1997). A risk-based approach for the management of total petroleum hydrocarbons in soil: A technical overview of the petroleum hydrocarbon risk assessment approach of

the TPH Criteria Working Group. http://www.aehs.com/publications/catalog/contents/tph.htm.

31. Twerdok, L. E. (1999). Development of toxicity criteria for petroleum hydrocarbon fractions in the petroleum hydrocarbon criteria working group approach for risk-based management of total petroleum hydrocarbons in soil. Drug and chemical toxicology, 22(1), 275–291. https://doi.org/10.3109/01480549909029736

32. U.S. Environmental Protection Agency (U.S. EPA). (2000). Risk characterization handbook (EPA 100-B-00-002). https://www.epa.gov/sites/default/files/2015-10/documents/osp_risk_characterization_handbook_2000.pdf

33. U.S. Environmental Protection Agency. (1989). Risk assessment guidance for Superfund: Volume I—Human health evaluation manual (Part A) (EPA/540/1-89/002). epa.gov/system/files/documents/2024-10/rags_a_508.pdf

34. U.S. Environmental Protection Agency. (1991). Risk assessment guidance for Superfund: Volume I—Human health evaluation manual (Part B, Development of risk-based preliminary remediation goals)—Interim (EPA/540/R-92/003). https://semspub.epa.gov/src/document/HQ/156739

35. U.S. Environmental Protection Agency. (2001). Risk assessment guidance for Superfund: Volume I—Human health evaluation manual (Part D, standardized planning, reporting, and review of Superfund risk assessments) (Publication No. 9285.7-47). https://semspub.epa.gov/src/document/HQ/175137.

36. U.S. Environmental Protection Agency. (2005). Guidelines for carcinogen risk assessment (EPA/630/P-03/001F). https://www.epa.gov/risk/guidelines-carcinogen-risk-assessment

37. U.S. Environmental Protection Agency. (2011). Highlights of the exposure factors handbook (EPA/600/R-10/030). https://semspub.epa.gov/work/HQ/190593.pdf

38. U.S. Environmental Protection Agency. (2017). Update for Chapter 5 of the Exposure Factors Handbook: Soil and dust ingestion (EPA/600/R-17/384F). https://www.epa.gov/sites/default/files/2018-01/documents/efh-chapter05_2017.pdf.

39. U.S. Environmental Protection Agency. (2019). Guidelines for human exposure assessment (EPA/100/B-19/001). https://www.epa.gov/sites/default/files/2020-01/documents/guidelines_for_human_exposure_assessment_final2019.pdf

40. United Nations Environment Programme (UNEP). (2011). Environmental assessment of Ogoniland. United Nations Environment Programme. https://www.unep.org/resources/report/environmental-assessment-ogoniland.

41. Yu, B., Yuan, Z., Yu, Z., & Xue-song, F. (2022). BTEX in the environment: An update on sources, fate, distribution, pretreatment, analysis, and removal techniques. Chemical Engineering Journal, 435, 134825. https://doi.org/10.1016/J.CEJ.2022.134825

42. Zahed, M. A., Salehi, S., Khoei, M. A., Esmaeili, P., & Mohajeri, L. (2024). Risk assessment of Benzene, Toluene, Ethylbenzene, and Xylene (BTEX) in the atmospheric air around the world: A review. Toxicology in Vitro, 98. https://doi.org/10.1016/j.tiv.2024.105825

43. Zeng, Y., Wang, S., Huang, F., Luo, Q., Ren, B., Abo El-Maati, M. F., & El-Sappah, A. H. (2025). Fate of polycyclic aromatic hydrocarbons in the phytoremediation of different hydrocarbon-contaminated soils with cotton, ryegrass, tall fescue, and wheat. Frontiers in Plant Science, 16, Article 1550234. https://doi.org/10.3389/fpls.2025.1550234

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryDataP12SensitivityRiskResultsNoFoVGICS0p00.xlsx.xls
- SupplementaryDataP11SensitivityRiskResultsPlantUptakeExcluded.xlsx.xls
- SupplementaryDataP10SensitivityRiskResultsLowFoVGICS0p01.xlsx.xls
- SupplementaryDataP9SensitivityRiskResultsBaselineFoVGICS0p25.xlsx.xls
- SupplementaryDataP8SensitivityRiskResultsHighHighFoVGICS0.50.xlsx.xls
- SupplementaryDataP3SensitivitySSTLHighVegFraction0.50.xls
- SupplementaryDataP4SensitivitySSTLReducedVegFraction0.10.xls
- SupplementaryDataP5SensitivitySSTLReducedVegFraction0.xls
- SupplementaryDataP6SensitivitySSTLReducedVegFraction0.25.xls
- SupplementaryDataP7SensitivitySSTLNoPlantUptakeModel.xlsx.xls
- SupplementaryDataS1RISC5Tier2SSTLModellingOutput.xlsx.xls
- SupplementaryDataS2RISC5Tier2SSTLModellingOutput.xlsx