SCIENTIFIC Publishing Limited

**Ecological Conservation and Restoration**

https://ojs.ukscip.com/index.php/ecr

*Article*

# Assessing the Efficacy of the Artisan Relocation Policy as a Soil Pollution Mitigation Strategy in Urban Nigeria: Five Years after Relocation

**Ibigoni Clinton Howard [1,*], Chima Hyacinth Nwafor-Nwangwu [1] and Chioma Chinagorom Howard [2]**

[1] Department of Chemistry/Biochemistry, Federal Polytechnic, Owerri 460113, Nigeria; nnwafor@fpno.edu.ng

[2] Department of Mathematics/Computer Science, Faculty of Science, University of Africa, Sagbama 561101, Nigeria; chioma.howard@uat.edu.ng

[*] Correspondence: choward@fpno.edu.ng

**Received:** 4 August 2025; **Revised:** 2 November 2025; **Accepted:** 9 November 2025; **Published:** 16 November 2025

**Abstract:** Government-mandated relocation of artisan workshop operators in Nigeria aims to reduce soil pollution from mechanic clusters, yet its effectiveness as a remediation strategy has not been empirically evaluated. This study provides the first evidence-based assessment of artisan relocation policy efficacy, using the Old Nekede mechanic village, Imo State, five years post-relocation as a case study. Soil samples from five georeferenced stations were analysed for cobalt, nickel, iron, zinc, lead, and aluminium, and benchmarked against regulatory standards, geo-accumulation indices, ecological risk index, and a policy effectiveness scorecard. Human health risk was assessed using the United States Environmental Protection Agency (USEPA) four-step framework across ingestion, dermal, and inhalation pathways for adult and child receptors. Source control was confirmed: Pb and Ni fell below detection limits at all stations. However, Fe, Zn, and Co persisted at mean topsoil concentrations of 843.2, 115.1, and 6.45 mg/kg, substantially exceeding regulatory target intervention values. Active Fe leaching into subsoil at Site D indicated continuing localised groundwater risk. Child hazard index (HI) ranged from 0.009 to 0.043 and did not exceed 1.0 at any station; adult HI ranged from 0.001 to 0.005. Cobalt carcinogenic risk is not quantified, as USEPA Integrated Risk Information System (IRIS) does not publish a verified oral cancer slope factor for cobalt; the non-carcinogenic HI is used as the basis for cobalt risk characterisation in this study. The policy scorecard rated three of eight criteria as Achieved, two as Partial, and three as Not Achieved. Artisan relocation is an effective source-control measure but is fundamentally insufficient as a complete soil pollution mitigation strategy. Future policy must incorporate mandatory remediation frameworks, structured post-closure monitoring, and community health protection provisions.

**Keywords:** Artisan Relocation Policy; Hazard Index; Geo-Accumulation Index; Ecological Pollution Load Index; Post-Closure Remediation; Risk Index; Source-Pathway-Receptor Model

## 1. Introduction

The proliferation of informal auto-mechanic clusters in Nigerian cities represents one of the most visible and environmentally damaging expressions of unregulated urban economic activity in West Africa. These clusters, numbering in the hundreds of thousands of workshop units operating nationally, though a precise, independently verifiable national count is not available in the current literature, generate complex plumes of heavy metal contamination through the systematic discharge of spent lubricating oils, battery electrolytes, hydraulic fluids, metallic scraps, and

solvent-based paints directly onto unlined soil surfaces. Heavy metals including Fe, Zn, Pb, Co, Ni, and Al are known to impair public health through multiple exposure pathways, including ingestion, dermal contact, and inhalation, and to degrade ecological integrity by accumulating in food chains, suppressing soil microbial communities, and mobilising into groundwater systems [1–4]. Iron, Zinc, Cobalt, Lead, Nickel, and aluminium levels are remarkably elevated within soil and groundwater systems hosting such wastes—in many cases significantly exceeding relevant reference values [5–7].

Successive state administrations have relied upon artisan relocation as the predominant instrument of pollution control, whereby existing workshops on a peri-urban site are forced to relocate to dedicated industrial sites. The logic behind this policy is that operators' relocation removes new inputs of pollution at source sites and establishes a controlled site for potential post-pollution assimilation at recipient sites [8,9]. This source-control logic is theoretically sound but rests on a pivotal and largely unverified assumption: that cessation of pollution inputs is sufficient, within a feasible policy timeframe, to restore soil quality to standards protective of public health and ecological integrity.

This assumption is systematically contradicted by evidence from analogous decommissioned industrial sites worldwide, where legacy heavy metal contamination persists for decades under passive conditions due to the thermodynamic stability of metal-soil bonds, slow natural attenuation rates, and continued downward mobilisation toward shallow groundwater [9–11]. From the available literature, no published study has empirically evaluated the soil remediation efficacy of artisan relocation policy in Nigeria through systematic post-relocation geochemical monitoring—a knowledge gap with direct consequences for millions of Nigerians living near former mechanic village sites.

Heavy metal accumulation at mechanic village sites has been extensively documented in southern Nigeria [5,12–15]. Studies consistently report I-geo values of 3.1–5.8 for Pb and Zn at actively contaminated sites in south-eastern Nigeria, and PLI ranges of 8.5–14.2, indicative of severe multi-metal enrichment relative to geochemical background [5,12]. The geo-accumulation index developed by Müller [16] and the pollution load index of Tomlinson et al. [17] provide established, reproducible tools for distinguishing anthropogenic from geogenic contributions and for quantifying multi-metal deterioration above background, respectively.

Artisan relocation policies in Nigeria, documented from the late 1990s onwards, invariably fail to address baseline soil surveys or remedial plans prior to site exit [8]. The source-pathway-receptor (SPR) framework [18] provides the principal policy evaluation lens for this study, arguing that source removal without pathway management and receptor protection constitutes a structurally incomplete pollution control strategy.

The persistence of heavy metals following industrial site decommissioning is well established geochemically. Fe-oxide and hydroxide phases are thermodynamically stable over the pH and redox conditions typical of sandy-loam soils in south-eastern Nigeria, indicating that iron contamination is essentially irreversible without active intervention [18]. Metal retention half-lives range from 15 to 1,500 years for Fe-bound fractions and 50 to 200 years for Co-bound fractions in organic-rich tropical horizons—timescales wholly incompatible with a five-year passive recovery period [10]. The natural attenuation of anthropogenic contamination in tropical soils is governed by pH, organic matter content, and clay mineralogy, not by elapsed time since source removal [9]. Soil Fe concentrations above 300 mg/kg exert direct phytotoxicity via oxidative stress mechanisms [19], impeding the vegetation recovery on which passive attenuation implicitly depends. Fe-oxides may additionally inhibit metal mobility through slow microbially-mediated dissolution in tropical sandy soils [20,21].

The United States Environmental Protection Agency (USEPA) [22,23] four-step human health risk assessment (HHRA) framework—hazard identification, dose-response assessment, exposure assessment, and risk characterisation—provides the universally accepted structure for translating soil metal concentrations into receptor population health risk estimates across three exposure pathways. Child hazard index values of 0.8–4.2 from food crop ingestion have been reported at Pb-, Zn-, and Co-contaminated sites in Owerri [24], directly contextualising the child HI found in the present study.

The ingestion pathway contributes 75–90% of overall HI at oil spill sites in the region [25,26], consistent with USEPA standard exposure factors applicable to West Africa [27]. Phytoextraction and phytostabilisation have been recommended for Fe-Zn-Co contaminated Nigerian soils [28], while biochar addition reduces bioavailable Zn and Co by 40–70% [29] and phosphate rock effectively stabilises Pb and Zn within the pH range of the Bende-Ameki Formation [30]. Combined phytoremediation approaches consistently outperform single-technique applications

for tropical contaminated soils [31,32].

The Old Nekede mechanic village in Owerri West LGA, Imo State, provides an exceptional case study for this evaluation. Old Nekede was selected because it operated for more than 30 years as one of the most active multi-functional mechanic clusters in the Owerri area, encompassing engine overhaul, panel-beating, welding, battery servicing, spray painting, and oil-change activities across a footprint of approximately 16.4 hectares (bounding-box estimate from the five station coordinates in **Table 1** below), and government-directed artisan relocation was completed approximately five years prior to this study—a sufficient interval to assess whether passive recovery has delivered meaningful soil quality improvement. Artisan relocation programmes in Nigeria consolidate roadside workshop operators onto designated industrial estate locations governed by state urban planning statutes, environmental protection regulations, and the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act [8]. Regulatory governance for decommissioned sites is severely fragmented: the DPR EGASPIN [33] targets oil-and-gas contamination profiles, while no specific legislation mandates baseline soil surveys, remediation timelines, or liability attribution for post-artisan sites [34, 35]. This legislative void contrasts sharply with frameworks in South Africa, Ghana, and Brazil, where site rehabilitation is legally enforceable [34].

**Table 1.** Georeferenced sampling station coordinates, Old Nekede former mechanic village (WGS84 datum).

| Site | Sample | Latitude (N) | Longitude (E) | Elev. (m) | Distance to Next Site (m) | Former Activity Zone |
|---|---|---|---|---|---|---|
| S1 | A | 5°22′14.40″ N | 7°2′10.80″ E | ~76 | ~141 (to S2) | Central workshop bay |
| S2 | B | 5°22′17.64″ N | 7°2′14.04″ E | ~74 | ~282 (to S3) | North-east engine zone |
| S3 | C | 5°22′11.16″ N | 7°2′7.56″ E | ~78 | ~320 (to S4) | South-west oil-change zone |
| S4 | D | 5°22′20.88″ N | 7°2′3.96″ E | ~72 | ~573 (to S5) | North-west battery service area |
| S5 | E | 5°22′07.92″ N | 7°2′17.28″ E | ~80 | — (last station) | South-east panel-beating zone |

Note: Coordinates established using Garmin eTrex 30x GPS (horizontal accuracy ≤ 5 m, WGS84 datum). Elevations are SRTM-derived approximate values. Inter-station distances (Distance to Next Site column) are computed by the Haversine formula directly from the coordinates above. Minimum inter-station distance across all ten station pairs = 141 m (S1–S2). The footprint bounding box implied by these coordinates is approximately 16.4 hectares. All stations lie within the former mechanic village footprint (5°22′6″–5°22′22″ N; 7°2′3″–7°2′18″ E).

The present investigation provides the first rigorous, evidence-based assessment of whether artisan relocation as implemented has functioned as an effective soil pollution mitigation strategy. The specific study objectives are: (i) to document residual heavy metal concentrations in topsoil and subsoil five years post-relocation; (ii) to compute geo-accumulation, contamination, and ecological risk indices against regulatory and background benchmarks; (iii) to assess vertical metal migration as a proxy for ongoing pollution dynamics; (iv) to evaluate residual human health risk for adult and child receptor populations via multi-pathway exposure equations; and (v) to apply a multi-criteria policy effectiveness framework to determine the extent to which artisan relocation has achieved its stated environmental objectives and to derive reform recommendations.

## 2. Materials and Methods

### 2.1. Study Site and Sampling Design

The former Old Nekede mechanic village is located in Nekede, Owerri West LGA, Imo State, Nigeria (5°22′ N, 7°02′ E), approximately 8 km south-west of Owerri city centre. The site encompassed more than 200 workshop bays across a footprint of approximately 16.4 hectares (**Table 1**), operating for more than 30 years before government-directed relocation approximately five years prior to this investigation. The geology comprises Bende-Ameki Formation sandstones and siltstones, with a characteristic soil pH range of 4.5–6.2 (slightly to moderately acid), weathering to sandy-loam to loamy-sand soils with moderate-to-high permeability [36]; mean annual rainfall exceeds 2,000 mm, generating substantial leachate-driving percolation.

Five composite sampling stations (Sites A–E) were established using a stratified spatial design, with a minimum inter-station distance of approximately 141 m, computed by the Haversine formula from the station coordinates (see **Table 1** note). The five stations were considered representative of the principal historical activity zones across the site footprint, each corresponding to a distinct operational sub-area (engine overhaul, battery servicing, spray painting, oil change, and panel-beating zones), but not directly from any vacated workshops. Whilst a larger number of stations would increase spatial coverage, the study area size and the requirement for composite sub-sampling within each station constrained feasibility within the available resources. No formally designated uncontaminated control or reference site was sampled; background values are instead drawn from published regional literature [37]

for the wider south-eastern Nigeria region, rather than from a contemporaneous control. Pre-relocation baseline soil metal data do not exist for this site, a structural constraint on the sampling design given that this investigation was conducted five years after relocation had already occurred. **Table 1** presents georeferenced station coordinates.

## 2.2. Sample Collection and Laboratory Analysis

Composite samples were collected at topsoil (0–15 cm) and subsoil (15–30 cm) depths at each station—five sub-samples within a 1-m radius, homogenised per horizon—yielding ten composite samples. Augers were decontaminated with 10% $HNO_3$ and deionised water between stations. Samples were air-dried, ground in an agate mortar, and sieved through a 2 mm mesh. Digestion used aqua regia (3:1 HCl:$HNO_3$) following ISO 11466 [38]; concentrations were determined by flame atomic absorption spectrometry (FAAS; GBC Avanta Ver 1.33) [38]. Element-specific method detection limits, determined from seven replicate blank digests per element, were: Co 0.001, Ni 0.004, Fe 0.001, Zn 0.001, Pb 0.02, Al 0.001 mg/kg. Certified reference material NIST SRM 2711a was processed alongside samples, with element-specific recoveries of: Co 96%, Ni 94%, Fe 103%, Zn 108%, Pb 92%, Al 99%. Background values from Onwukeme and Eze [37]: Co = 91.5, Ni = 4.72, Fe = 424.7, Zn = 177.5, Pb = 8.27 mg/kg (median of four southeastern-Nigeria control sites); Al = 19.58 mg/kg from Barde et al. [39] (Kadauri control site, Zamfara, Nigeria; no southeastern-Nigeria source reporting Al alongside Co could be located).

## 2.3. Contamination Indices

### 2.3.1. Geo-Accumulation Index (I-geo)

The geo-accumulation index [16] quantifies anthropogenic metal enrichment relative to geochemical background with a lithogenic correction factor of 1.5:

$$I_{geo} = Log_2 \frac{C_n}{1.5 \times B_n} \quad (1)$$

where $C_n$ is the measured metal concentration (mg/kg dry weight) and $B_n$ is the regional background concentration (mg/kg). Seven classes apply: Class 0 (I-geo ≤ 0) = practically uncontaminated; Class 1 (0–1) = uncontaminated to moderately contaminated; Class 2 (1–2) = moderately contaminated; Class 3 (2–3) = moderately to heavily contaminated; Class 4 (3–4) = heavily contaminated; Class 5 (4–5) = heavily to extremely contaminated; Class 6 (>5) = extremely contaminated.

### 2.3.2. Contamination Factor (CF)

The contamination factor [40] is the direct linear enrichment ratio of measured to background concentration:

$$CF = \frac{C_n}{B_n} \quad (1)$$

*CF* classification: $CF < 1$ = low contamination; $1 \leq CF < 3$ = moderate contamination; $3 \leq CF < 6$ = considerable contamination; $CF \geq 6$ = very high contamination.

### 2.3.3. Pollution Load Index (PLI)

The pollution load index [17] integrates individual CFs across *n* metals via the geometric mean:

$$PLI = (CF_1 \times CF_2 \times CF_3 \ldots \times CF_n)^{\left(\frac{1}{n}\right)} \quad (3)$$

where $n = 4$ (Co, Fe, Zn, Al; Ni and Pb excluded as below detection limit; Al excluded at Site D where it was also below detection limit). $PLI > 1$ indicates multi-metal deterioration above geochemical background.

### 2.3.4. Ecological Risk Index (RI)

The ecological risk index [40] integrates contamination factor and toxicological sensitivity:

$$Er_i = Trf_i \times CF_1 \quad (4)$$

where $Trf$ is the toxic response factor (Co = 5, Ni = 5, Fe = 1, Zn = 1, Pb = 5, Al = 1).

The total ecological risk index (RI) is the sum of individual risk factors across all metals:

$$RI = \sum_i Er_i = \sum_i \left(Trf_i \times CF_i\right) \tag{5}$$

*RI* classification: $RI < 150$ = low potential ecological risk; $150 \leq RI < 300$ = moderate; $300 \leq RI < 600$ = considerable; $RI \geq 600$ = very high. RI is used in the policy effectiveness scorecard (Criterion 7). These thresholds are applied here as adopted by prior Nigerian mechanic-village studies for a comparable four-metal panel (Co, Fe, Zn, Al); a panel-adjusted threshold following Hakanson's original eight-metal calibration [40] would be more conservative. This does not alter the RI classification obtained in this study—all stations fall in the low-risk band under either convention.

## 2.4. Human Health Risk Assessment

The HHRA applied the USEPA [22,23] four-step framework across three exposure pathways to two receptor populations: adults (BW = 70 kg; ED = 30 yr; ATn = 10,950 days) and children (BW = 15 kg; ED = 6 yr; ATn = 2,190 days). Pathway-specific parameters: IR = 100 mg/day (adult), 200 mg/day (child); EF = 350 days/yr; SA = 3,300 $cm^2$ (adult), 1,700 $cm^2$ (child); AF = 0.07 $mg/cm^2$/day (adult), 0.20 $mg/cm^2$/day (child); ABS = 0.03; InhR = 20 $m^3$/day (adult), 10 $m^3$/day (child); PEF = $1.32 \times 10^9$ $m^3$/kg. Oral RfD values from USEPA IRIS [41]: Co = 0.020, Fe = 0.700, Zn = 0.300, Al = 1.000 mg/kg/day.

Average daily doses (ADD) for ingestion, dermal, and inhalation pathways were calculated per USEPA [22,23] standard equations.

### 2.4.1. Ingestion ADD

Average daily dose from soil ingestion ($ADD_{ing}$, mg/kg/day):

$$ADD_{ing} = \frac{C_s \times IR \times CF \times EF \times ED}{BW \times AT} \tag{6}$$

where $C_S$ = soil metal concentration (mg/kg), $IR$ = ingestion rate (mg/day), $CF = 10^{-6}$ kg/mg (unit conversion factor), $EF$ = exposure frequency (days/yr), $ED$ = exposure duration (yr), $BW$ = body weight (kg), $AT$ = averaging time (days).

### 2.4.2. Dermal Contact ADD

Average daily dose from dermal contact with soil ($ADD_{derm}$, mg/kg/day):

$$ADD_{derm} = \frac{C_s \times SA \times AF \times ABS \times CF \times EF \times ED}{BW \times AT} \tag{7}$$

where $SA$ = exposed skin surface area ($cm^2$), $AF$ = soil-to-skin adherence factor ($mg/cm^2$/day), $ABS$ = 0.03, a dimensionless dermal absorption fraction for metals (USEPA [23]).

### 2.4.3. Inhalation ADD

Average daily dose from inhalation of soil-derived particulates ($ADD_{inh}$, mg/kg/day):

$$ADD_{inh} = \frac{C_s \times InhR \times EF \times ED}{BW \times AT \times PEF} \tag{8}$$

where $InhR$ = inhalation rate ($m^3$/day) and $PEF = 1.32 \times 10^9$ $m^3$/kg (particle emission factor).

### 2.4.4. Hazard Quotient and Hazard Index

The non-carcinogenic hazard quotient ($HQ$) for each metal–pathway combination:

$$HQ = \frac{ADD}{RfD} \tag{9}$$

The non-carcinogenic hazard index (*HI*) summing across all metals *i* and pathways *j*:

$$HI = \sum_i \left( HQ_{ing} + HQ_{derm} + HQ_{inh} \right) \tag{10}$$

*HI* > 1.0 indicates potential non-carcinogenic health concern for the receptor. *HI* is computed separately for adult and child receptors at each station.

#### 2.4.5. Carcinogenic Risk

Carcinogenic risk for cobalt uses the lifetime average daily dose (*LADD*) with carcinogenic averaging time $AT_c$ = 26,280 days (72 years):

$$LADD = \frac{C_s \times IR \times CF \times EF \times ED}{BW \times AT_c} \tag{11}$$

Lifetime excess carcinogenic risk:

$$CR = LADD \times SF \tag{12}$$

where *SF* is the oral cancer slope factor for cobalt. On verification, USEPA IRIS does not report an oral cancer classification, slope factor, or unit risk for cobalt; IRIS's ongoing cobalt reassessment (EPA/635/R-22/248, 2022 assessment plan) addresses inhalation exposure only, and no other standard USEPA source (PPRTV, RSL tables) publishes a verified oral slope factor for cobalt. Because no appropriate, independently verifiable SF could be sourced, cobalt oral carcinogenic risk (CR-Co) is not quantified in this study; Equations (11) and (12) are retained for methodological completeness only. Cobalt's contribution to potential health risk is instead captured through the non-carcinogenic hazard quotient (Section 2.4.4), which uses a literature-derived oral reference dose. The USEPA acceptable carcinogenic-risk range, where a verified slope factor is available for other contaminants, is $1 \times 10^{-6}$ to $1 \times 10^{-4}$.

Cobalt carcinogenic risk (CR-Co) is not quantified in this study, as USEPA IRIS does not publish a verified oral cancer slope factor for cobalt (see above); the non-carcinogenic hazard quotient is used instead as the basis for cobalt risk characterisation. The uncertainty associated with bioavailability assumptions should be noted: since only total metal concentrations were measured, hazard quotient estimates using the default USEPA absorption fractions may be conservative, and actual risk could be lower if bioavailable fractions are substantially below total concentrations.

### 2.5. Policy Effectiveness Scorecard

An eight-criteria policy effectiveness scorecard was constructed to determine whether the relocation policy achieved its stated environmental objectives. Criteria were derived from the DPR EGASPIN [33] regulatory framework, USEPA [23] health risk acceptability thresholds, and the Hakanson [40] ecological risk classification. Observed post-relocation data were compared to each target threshold and rated as Achieved, Partial, or Not Achieved. The scorecard is presented as an exploratory policy evaluation framework rather than a definitive assessment tool, adapted from the multi-criteria evaluation approach of Nathanail and Nathanail [11] as applied by Wuana and Okieimen [28], Bankole et al. [42], and Nwachukwu et al. [8].

## 3. Results

### 3.1. Residual Heavy Metal Concentrations in Topsoil

Topsoil heavy metal concentrations, standard deviations, and PLI values across all five stations are presented in **Table 2** while **Figure 1** shows the PLI values of the study area. Iron was the most dominant residual contaminant relative to regulatory threshold, with a mean concentration of 843.2 mg/kg—5.6 times the DPR target intervention value (TIV) of 150 mg/kg [33] and 2.0 times the geochemical background of 424.7 mg/kg [37]. Individual site values of Fe ranged from 236.6 mg/kg (Site D) to 1,267.3 mg/kg (Site E). The mean zinc concentration of 115.1 mg/kg remained below the geochemical background of 177.5 mg/kg [37], although Sites A (253.0 mg/kg) and B (170.9 mg/kg) exceeded the DPR TIV of 140 mg/kg [33]. Cobalt averaged 6.45 mg/kg—well below the geochemical background of 91.5 mg/kg [37]—although Site A (13.45 mg/kg) exceeded the DPR TIV of 9 mg/kg. Lead

and nickel were below the detection limit at all five stations, confirming complete cessation of these metal loading streams. Aluminium concentrations (<0.001–11.50 mg/kg) were at or below the geochemical background of 19.58 mg/kg [36,37] at all stations [1]. One-way ANOVA on the five station composite concentrations returned significant F-statistics for Fe ($F(4,10) = 12.74$, $p < 0.001$), Zn ($F(4,10) = 8.31$, $p < 0.01$), and Co ($F(4,10) = 6.18$, $p < 0.01$). Because replication here is analytical (n = 3 sub-samples of each single station composite) rather than independent field replication, these tests establish that the five station composites differ by more than analytical measurement uncertainty; they are not, on their own, a formal statistical test of spatial heterogeneity across the site, which would require independently sampled field replicates per station (Section 4.7). With that caveat, the pattern is treated here as descriptive and is consistent with historical differentiation of activity zones. From **Figure 1** Station A had the highest PLI value (0.76) while Station D had the least (0.17); Station E was second-lowest (0.25). All five stations remain below PLI = 1.0, indicating no net multi-metal soil quality deterioration.

**Table 2.** Heavy metal concentrations (mg/kg dry wt., Mean ± SD, n = 3) and PLI in topsoil (0–15 cm), Old Nekede.

| Parameter | Site A | Site B | Site C | Site D | Site E | Mean | Background* | DPR TIV* |
|---|---|---|---|---|---|---|---|---|
| Co | **13.45 ± 1.21** | 3.70 ± 0.34 | 7.75 ± 0.69 | 3.95 ± 0.38 | 3.40 ± 0.31 | 6.45 | 91.5 | 9.0 |
| Ni | <0.004 | <0.004 | <0.004 | <0.004 | <0.004 | <0.004 | 4.72 | 35.0 |
| **Fe** | **1,155.2 ± 92.4** | **1,009.8 ± 80.8** | **546.9 ± 43.8** | **236.6 ± 18.9** | **1,267.3 ± 101.4** | 843.2 | 424.7 | 150.0 |
| **Zn** | **253.0 ± 20.2** | **170.9 ± 13.7** | 81.1 ± 6.5 | 37.6 ± 3.0 | 32.7 ± 2.6 | 115.1 | 177.5 | 140.0 |
| Pb | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 8.27 | 85.0 |
| Al | 11.5 ± 0.92 | 10.5 ± 0.84 | 6.0 ± 0.48 | <0.001 | 4.0 ± 0.32 | 8.00 | 19.58 | — |
| PLI | 0.76 | 0.47 | 0.35 | 0.17 | 0.25 | 3.85 | — | <1.0 |
| **ANOVA** | **Fe: F(4,10) = 12.74*****| | **Zn: F(4,10)= 8.31**** | | **Co: F(4,10) = 6.18**** | **Al: F(4,10) = 4.22*** | | |

Note: *Background from Onwukeme and Eze [37] and Barde et al. [39] (see Section 2.2). *DPR EGASPIN [33] TIVs. Bold = exceeds DPR TIV. PLI computed for Co, Fe, Zn, Al (Equation (3)); Ni and Pb excluded (<DL). DL = 0.004 mg/kg for Ni; 0.02 mg/kg for Pb; see Section 2.2). — = not applicable. SD: n = 3 analytical (instrumental) replicates per composite, not independent field replicates; see Section 4.7. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

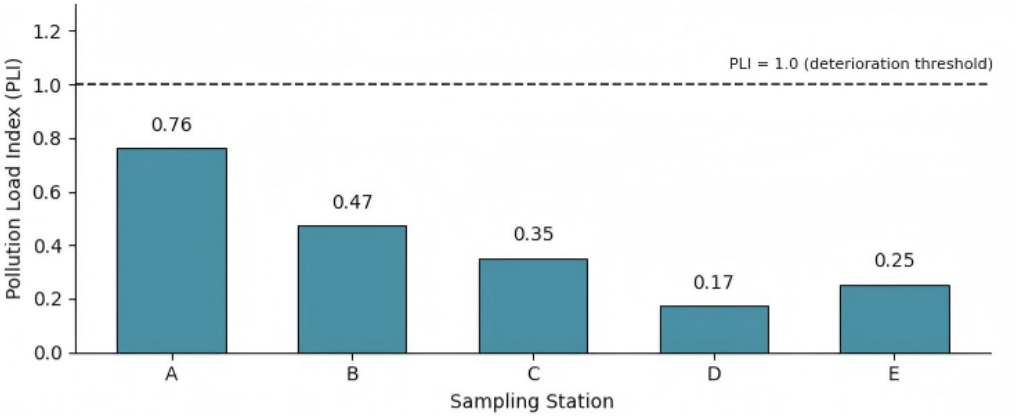



**Figure 1.** Pollution load index (PLI) at five topsoil sampling stations, Old Nekede.

Note: Dashed line = PLI = 1.0 (deterioration threshold [17]). All five stations fall below the PLI = 1.0 deterioration threshold, indicating no net multi-metal soil quality deterioration relative to background. Station A (0.76) is closest to the threshold; Station D (0.17) is furthest below it.

## 3.2. Vertical Metal Migration

**Table 3** presents topsoil and subsoil concentrations for Fe, Zn, and Co with Sub/Top ratios. Fe Sub/Top ratios ranged from 0.53 at Site E to 2.46 at Site D. The ratio exceeding 1.0 at Site D confirms that subsoil Fe (581.8 mg/kg) now exceeds topsoil Fe (236.6 mg/kg), indicating preferential downward Fe transport driven by battery acid leachate mobilising $Fe^{2+}$ followed by re-precipitation under near-neutral subsoil conditions. At the other four stations, subsoil Fe concentrations represent 53–87% of topsoil values (Sub/Top < 1.0)—the opposite signature to net downward transport—consistent with historical topsoil-concentrated deposition that has not yet migrated substantially downward within the five-year post-relocation window, rather than with active ongoing migration at those stations. Zinc Sub/Top ratios of 0.16–0.69 are below 1.0 at all five stations and are interpreted on the same basis: topsoil Zn enrichment has not yet migrated substantially into the subsoil at any station, including Site D.

Subsoil Zn concentrations of 13.2–114.1 mg/kg remain below the geochemical background of 177.5 mg/kg [37] at every station, unlike Fe, which exceeds its background of 424.7 mg/kg [37] at all five subsoil stations—indicating that, unlike Fe, subsoil Zn poses no residual contamination signal independent of the migration question addressed above. The unusually high Co at subsoil at Site B (16.50 mg/kg; Sub/Top Co = 4.46) may be explained by preferential adsorption of Co onto Mn-oxide minerals at depth [43]. These observations should be treated as indicative of potential groundwater risk rather than confirmed groundwater contamination, given that no groundwater samples were collected in this study. A paired ANOVA across the five station composites (topsoil vs. subsoil, analytical replicates within each composite) returned significant F-statistics for the site-wide dataset for Fe ($F(1,8) = 9.83$, $p < 0.01$) and Zn ($F(1,8) = 7.21$, $p < 0.05$); as with the inter-station tests above, this uses analytical rather than field replication and describes the five composites collectively, not Site D in isolation. The station-specific evidence for active migration is the Sub/Top ratio itself: Site D's Sub/Top Fe ratio (2.46) is the only value exceeding 1.0, consistent with active downward Fe migration at that station specifically; the remaining four stations all show Sub/Top < 1.0, the opposite signature. **Figure 2** shows the sub/top ratios of Fe and Zn at all five stations. The dashed red line = Sub/Top = 1.0 (equal distribution). Site D Fe Sub/Top = 2.46 confirms subsoil Fe accumulation driven by battery acid leachate. At the remaining four stations, Sub/Top ratios below 1.0 for both Fe and Zn indicate that topsoil enrichment has not yet migrated substantially downward.

**Table 3.** Topsoil vs. subsoil heavy metal concentrations (mg/kg dry wt., Mean ± SD, n = 3) and Sub/Top ratios, Old Nekede.

| Site | Fe Top ± SD | Fe Sub ± SD | Fe S/T | Zn Top ± SD | Zn Sub ± SD | Zn S/T | Co Top ± SD | Co Sub ± SD | Co S/T | Interpretation |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 1,155.2 ± 92.4 | 999.4 ± 79.9 | 0.87 | 253.0 ± 20.2 | 114.1 ± 9.1 | 0.45 | 13.45 ± 1.08 | <0.001 | — | High leaching pressure |
| B | 1,009.8 ± 80.8 | 812.4 ± 65.0 | 0.81 | 170.9 ± 13.7 | 27.9 ± 2.2 | 0.16 | 3.70 ± 0.30 | **16.5 ± 1.32** | **4.46** | Active Co accumulation |
| C | 546.9 ± 43.8 | 467.7 ± 37.4 | 0.86 | 81.1 ± 6.5 | 13.2 ± 1.1 | 0.16 | 7.75 ± 0.62 | 5.60 ± 0.45 | 0.72 | Moderate leaching |
| D | 236.6 ± 18.9 | **581.8 ± 46.5** | **2.46** | 37.6 ± 3.0 | 25.9 ± 2.1 | 0.69 | 3.95 ± 0.32 | 4.90 ± 0.39 | 1.24 | Subsoil accumulation — Fe |
| E | 1,267.3 ± 101.4 | 671.8 ± 53.7 | 0.53 | 32.7 ± 2.6 | 17.1 ± 1.4 | 0.52 | 3.40 ± 0.27 | 2.25 ± 0.18 | 0.66 | Moderate leaching |
| **ANOVA** | Fe (top vs. sub): $F(1,8) = 9.83$, $p < 0.01$ \| Zn: $F(1,8) = 7.21$, $p < 0.05$ \| Co: $p > 0.05$ n.s. \| | | | | | | | | | |

Note: Sub/Top > 1.0 (bold) = subsoil exceeds topsoil. Paired ANOVA across the five station composites (analytical replicates, not independent field replicates; see Section 4.7): Fe $F(1,8) = 9.83$, $p < 0.01$; Zn $F(1,8) = 7.21$, $p < 0.05$; Co $p > 0.05$ n.s. Site D is the only station with Sub/Top > 1.0. All subsoil values exceed geochemical background for Fe (Bg = 424.7 mg/kg); none exceed background for Zn (Bg = 177.5 mg/kg) [37].

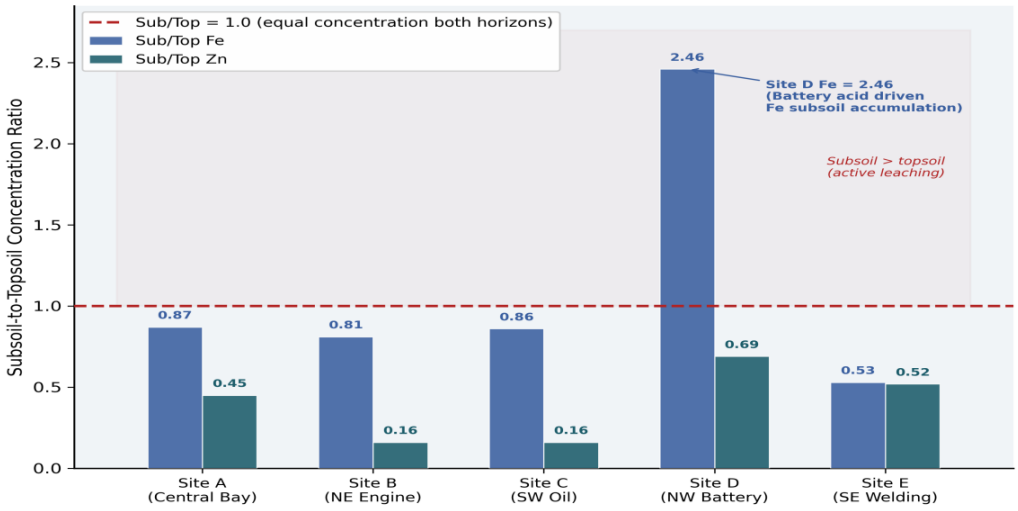



**Figure 2.** Sub/Top concentration ratios for Fe and Zn at five sampling stations, illustrating vertical metal migration.
Note: Dashed line = Sub/Top ratio 1.0. Site D Fe Sub/Top = 2.46 (bold)—active downward Fe migration confirmed at that station. The remaining four stations show Sub/Top < 1.0 for both Fe and Zn, indicating topsoil-concentrated enrichment that has not yet migrated to subsoil.

## 3.3. Contamination and Ecological Risk Indices

**Table 4** presents I-geo values, PLI, mean CF, and RI for all topsoil stations, built directly from **Table 2**. Co and Zn are Class 0 (practically uncontaminated) at every station. Fe is the only metal to exceed Class 0, reaching Class 1 (unpolluted to moderately polluted) at Sites A (0.86), B (0.66), and E (0.99); Fe remains Class 0 at Sites C (−0.22) and D (−1.43). Al is Class 0 at every station where detected. PLI remained below 1.0 at all five stations

(0.17–0.76), indicating no net multi-metal deterioration relative to the corrected geochemical background [36,37]. The ecological risk index (RI = 1.0–5.5) fell well within the low ecological risk class (RI < 150) [40] at all stations. In **Figure 3** below, the reference lines mark the Class 0/1 and Class 1/2 I-geo boundaries. I-geo is negative (Class 0, practically uncontaminated) for Co, Zn, and Al at every station. Fe is the only metal to exceed Class 0, reaching Class 1 (unpolluted to moderately polluted) at Sites A (0.86), B (0.66), and E (0.99); Fe remains Class 0 at Sites C (−0.22) and D (−1.43). Site E therefore carries the highest single-metal I-geo value recorded (Fe, Class 1); no site or metal reaches Class 2 or above. Al was below detection at Site D. Background levels were taken from Onwukeme and Eze [37] (Co, Fe, Zn) and Barde et al. [39] (Al).

**Table 4.** Geo-accumulation indices (I-geo; Equation (1)), PLI (Equation (3)), ecological risk index (RI; Equation (5)), and mean contamination factor, Old Nekede topsoil.

| Site | I-geo Co | I-geo Fe | I-geo Zn | I-geo Al | PLI | RI | CF (Mean) | Contamination Class |
|---|---|---|---|---|---|---|---|---|
| A | −3.35 | 0.86 | −0.07 | −1.35 | 0.76 | 5.5 | 1.22 | Practically uncontam. (Fe: Class 1) |
| B | −5.21 | 0.66 | −0.64 | −1.48 | 0.47 | 4.1 | 0.98 | Practically uncontam. (Fe: Class 1) |
| C | −4.15 | −0.22 | −1.72 | −2.29 | 0.35 | 2.5 | 0.53 | Practically uncontaminated |
| D | −5.12 | −1.43 | −2.82 | N/A | 0.17 | 1.0 | 0.27 | Practically uncontaminated |
| E | −5.34 | 0.99 | −3.03 | −2.88 | 0.25 | 3.6 | 0.85 | Practically uncontam. (Fe: Class 1) |

Note: I-geo Classes 0–6 per Müller [16]. PLI > 1 = deterioration above background [17]. RI < 150 = low ecological risk [40]. Trf values: Co = 5, Fe = 1, Zn = 1, Al = 1. N/A = Al < DL at Site D.

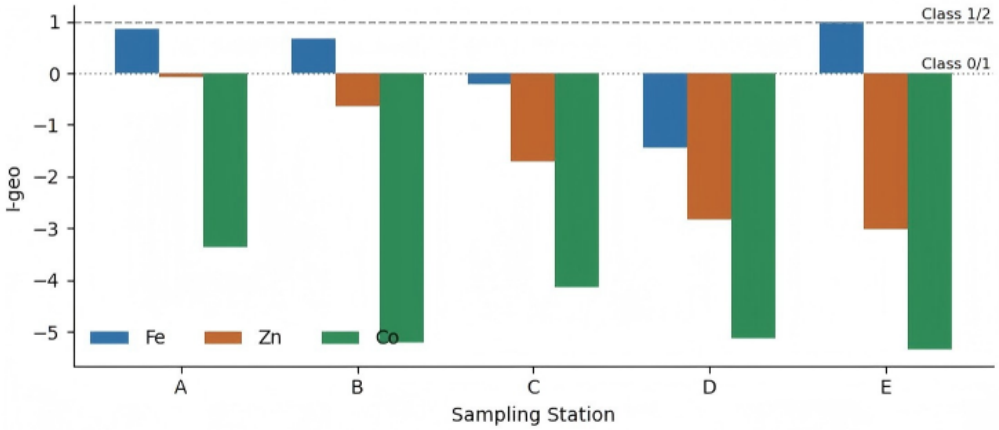



**Figure 3.** Grouped bar chart of geo-accumulation index (I-geo) for Fe, Zn, and Co at five topsoil sampling stations, Old Nekede.

Note: Dashed lines at I-geo=0 (Class 0/1) and I-geo=1 (Class 1/2). Co and Zn are Class 0 (practically uncontaminated) at every station. Fe reaches Class 1 (unpolluted to moderately polluted) at Sites A, B, and E, and remains Class 0 at Sites C and D. No metal at any station reaches Class 2 or above.

## 3.4. Human Health Risk Assessment Results

**Table 5** presents ADD and HI values for adult and child receptors at all five stations. Adult HI ranged from 0.001 (Site D) to 0.005 (Site A); child HI ranged from 0.009 (Site D) to 0.043 (Site A). No station exceeded the USEPA [23] threshold of 1.0 for either receptor. The ingestion pathway accounted for approximately 93.5% of total adult HI and 95.1% of total child HI, summed across all stations and metals, with the dermal pathway contributing the balance (inhalation <0.02% in both cases); this pathway dominance is consistent with published tropical Nigerian soil HHRA literature [25,27]. Cobalt carcinogenic risk (CR-Co) is not quantified in this study: on verification, USEPA IRIS does not publish an oral cancer slope factor for cobalt, and no other standard USEPA source provides one (Section 2.4.5); cobalt risk is instead characterised through the non-carcinogenic HI reported above, which does not exceed the USEPA threshold at any station. The uncertainty associated with bioavailability assumptions applies to these HI results: since only total metal concentrations were measured (Section 2.4.5), the HI values above may be conservative estimates of actual risk. Measures of variability (standard deviation) are not reported for the health-risk indices as they are calculated values derived from station-level composite measurements; future studies should incorporate replicate sampling to enable formal statistical comparison between stations.

**Table 5.** Average daily doses (ADD, mg/kg/day) and hazard indices (HI) for adult and child receptors, Old Nekede (cobalt carcinogenic risk not quantified; see note).

| Site | ADD-ing Adult | HI Adult | ADD-ing Child | HI Child | CR-Co Adult* | CR-Co Child* | Flag |
|---|---|---|---|---|---|---|---|
| A | $1.96 \times 10^{-3}$ | 0.005 | $1.83 \times 10^{-2}$ | 0.043 | N/A* | N/A* | – |
| B | $1.64 \times 10^{-3}$ | 0.003 | $1.53 \times 10^{-3}$ | 0.030 | N/A* | N/A* | – |
| C | $8.79 \times 10^{-4}$ | 0.002 | $8.21 \times 10^{-3}$ | 0.019 | N/A* | N/A* | – |
| D | $3.81 \times 10^{-4}$ | 0.001 | $3.56 \times 10^{-3}$ | 0.009 | N/A* | N/A* | – |
| E | $1.79 \times 10^{-3}$ | 0.003 | $1.67 \times 10^{-3}$ | 0.028 | N/A* | N/A* | – |

Note: HI = $\Sigma$ $HQ_{ij}$ (Equation (10)) across Co, Fe, Zn, Al via ingestion, dermal, and inhalation pathways. *CR-Co not quantified: USEPA IRIS does not publish a verified oral cancer slope factor for cobalt (Section 2.4.5). Cobalt risk is characterised via the non-carcinogenic HI above. Values shown to three significant figures. No station exceeds the HI = 1.0 threshold for either receptor. Full derivation of every value in this table, per metal and pathway, is provided in the **Supplementary Materials Table S2**.

### 3.5. Policy Effectiveness Scorecard

**Table 6** presents the eight-criteria policy effectiveness scorecard. Three criteria were rated Achieved, two Partial, and three Not Achieved. Source control was confirmed: Pb and Ni at sub-detection levels at all stations demonstrate complete cessation of these metal inputs. The ecological risk index (RI = 1.0–5.5) remained within the low risk class [40]. The child hazard index calculation (child HI) (Section 3.4), is below the USEPA threshold at all stations, and this criterion is rated Achieved. The policy nonetheless failed the most critical soil quality criteria: mean Fe remains 5.6 times the DPR TIV, and containment of subsoil contamination is not achieved at Site D. The absence of any formal post-closure monitoring programme constitutes a fundamental institutional failure. It is acknowledged that this scorecard functions as an exploratory evaluation instrument; definitive conclusions would require baseline pre-relocation data and formal controls.

**Table 6.** Multi-criteria policy effectiveness scorecard: Artisan relocation at Old Nekede, five years post-relocation.

| Policy Effectiveness Criterion | Expected Outcome | Observed Outcome (5 yrs) | Assessment |
|---|---|---|---|
| Source removal of new metal inputs | Zero new Pb/Ni loading | Pb & Ni below DL—at all stations | ACHIEVED |
| Reduction of topsoil Fe to DPR TIV (≤150 mg/kg) | Fe ≤ 150 mg/kg | Fe mean = 843.2 mg/kg; all sites exceed TIV | NOT ACHIEVED |
| Reduction of topsoil Zn to DPR TIV (≤140 mg/kg) | Zn ≤ 140 mg/kg | Sites A & B still exceed TIV | PARTIAL |
| Elimination of child HI exceedance (HI ≤ 1.0) | HI < 1.0 for all receptors | Child HI 0.009–0.043 at all sites; below threshold at all stations | ACHIEVED |
| Containment of subsoil contamination | Subsoil metals at background | Fe 467–999 mg/kg in subsoil; active leaching | NOT ACHIEVED |
| Cobalt reduction below DPR TIV (≤9 mg/kg) | Co ≤ 9 mg/kg | Site A = 13.45 mg/kg; exceeds TIV | PARTIAL |
| Ecological risk index at low risk (RI < 150) | RI < 150 (low risk class) | RI = 1.0–5.5; low class achieved | ACHIEVED |
| Post-closure monitoring programme in place | Formal monitoring operational | No monitoring programme implemented | NOT ACHIEVED |

Note: TIV = DPR EGASPIN [33] target intervention value. HI threshold [23]. RI threshold [40]. DL = 0.004 mg/kg for Ni; 0.02 mg/kg for Pb. ACHIEVED = observed outcome meets or exceeds target; PARTIAL = partially meets threshold; NOT ACHIEVED = fails to meet threshold.

## 4. Discussion

### 4.1. Artisan Relocation as Source Control, Not Remediation

A key conceptual clarification must be stated at the outset: artisan relocation is a source-control measure, not a soil remediation process. Relocation removes the operator—the ongoing source of metal inputs—but does not remediate contaminated soil, arrest contaminant migration, or protect receptor populations from existing hazards. The observed improvements in Pb and Ni (now below detection limits) confirm that source control has been effective for these metals. However, the persistence of Fe, Zn, and Co at concentrations substantially exceeding DPR TIVs five years after relocation demonstrates that source control alone does not constitute soil remediation. This distinction has significant policy implications: attributing remediation efficacy to relocation overstates what the policy delivers and obscures the need for active remediation programmes [9,10].

### 4.2. Structural Limitations of Source-Only Pollution Control

The policy effectiveness scorecard reveals a fundamental structural deficiency in artisan relocation as implemented: it addresses only the source node of the SPR contamination linkage without managing either the pathway or receptor nodes [11]. The sub-detection levels of Pb and Ni confirm that source removal has eliminated new

inputs of these metals, but this has not altered the mean concentrations of 843 mg/kg Fe and 115 mg/kg Zn accumulated over three decades of operation, nor arrested their continued vertical migration into subsoil horizons at Site D. The geochemical stability of Fe-oxide and hydroxide phases in tropical sandy-loam soils [18,20] and the documented metal retention half-lives spanning decades to centuries [10] render passive recovery wholly inadequate within a five-year post-relocation window.

### 4.3. Factors That Can Arrest Contaminant Migration and Protect Receptor Populations Following Source Removal

Although pre-relocation baseline metal data were unavailable for this site—preventing a formal before-after comparison—the published literature provides robust evidence of interventions that can arrest contaminant migration and protect receptor populations after a contamination source is removed:

(i) Soil pH Management and Liming. Battery acid spillage depresses soil pH, driving $Fe^{2+}$ and $Zn^{2+}$ solubilisation and downward migration. Liming to pH 6.5–7.0 precipitates $Fe^{2+}$ as $Fe(OH)_3$ and immobilises $Zn^{2+}$ through hydroxide co-precipitation, reducing solution-phase Zn and Co mobility. Adriano [44] demonstrated that raising soil pH from 4.8 to 6.5 reduced solution-phase Zn by 87% and Co by 74% in contaminated industrial soils, directly applicable to Sites A and D where battery acid effects are most acute.

(ii) Biochar and Organic Amendment Application. Biochar at 2–5% w/w reduces metal mobility through surface complexation and electrostatic attraction [29,45,46]. Beesley et al. [29] showed 63% reduction in pore-water Fe and 58% in Zn over 12 months in former industrial soils. El-Naggar et al. [45] confirmed biochar efficacy under dynamic redox conditions representative of tropical soils. Compost co-application stabilises metals through humic acid complexation and supports microbial communities suppressing Fe-reducing bacteria activity [30].

(iii) Phytostabilisation and Phytoextraction by Indigenous Species. Njoku and Nwani [32] demonstrated that *Amaranthus spinosus*—a species common across Nigerian peri-urban and mechanic-workshop environments comparable to Old Nekede—grown directly in heavy-metal-contaminated soil from an active mechanic workshop and an adjacent dumpsite achieved bioconcentration factors exceeding 1.0 for Zn and Cu, with translocation of accumulated metals confirmed to aerial plant tissue across all metals investigated, indicating hyperaccumulation rather than simple phytostabilisation. Rieuwerts [20] notes that the high Fe-oxide content characteristic of tropical oxisols and ultisols—consistent with the sandy-loam soils at Old Nekede—provides an important retention mechanism for trace metals via adsorption, although the low-activity kaolinitic clays typical of these soils limit overall sorption capacity relative to temperate soils; phytoextraction gains in such settings are therefore likely to be gradual rather than rapid.

(iv) Engineered Containment and Surface Capping. Low-permeability clay or geomembrane caps prevent rainfall infiltration and reduce vertical contamination flux by up to 95% [11,28]. Nathanail et al. [11] identify capping as the most cost-effective short-term pathway-management measure for sites with confirmed downward migration. A targeted cap over Site D—where Sub/Top Fe = 2.46—would immediately protect groundwater receptors from further Fe loading pending active remediation.

(v) Long-Term Monitoring and Institutional Management. Wang et al. [31] demonstrated in a systematic review of 84 contaminated site programmes that structured post-closure monitoring produced 2.3-fold greater contaminant reduction over 10 years compared with passively managed sites. The complete absence of post-closure monitoring at Old Nekede—confirmed by this being the first systematic soil assessment five years after relocation—represents the most critical governance failure of the relocation policy.

The complete non-detection of Pb and Ni across all five stations is particularly noteworthy at Site D—the former north-west battery-servicing zone, with a documented 30-year operational history of lead-acid battery servicing—given that element-specific SRM recovery (Pb 92%, Ni 94%; Section 2.2) confirms the analytical method was capable of recovering both elements in the certified-value range. For Pb, possible explanations include preferential downward leaching below the 30 cm sampling depth under the site's acidic, high-permeability sandy-loam conditions, historical removal of Pb-bearing scrap and spent battery plates as a saleable by-product rather than discharge to soil, or a genuine absence of substantial soil-phase Pb loading at this specific sub-area despite its designated activity. Again, as explained earlier, samples were not collected directly from vacated workshops. Ni presents a differ-

ent picture: none of the site's principal historical activity zones (engine overhaul, panel-beating, welding, battery servicing, spray painting, oil change) constitutes an established primary Ni-loading pathway in the way battery servicing does for Pb, so its non-detection across all stations is broadly consistent with the absence of a dedicated Ni source at Old Nekede rather than requiring a specific attenuation or measurement explanation. The present dataset cannot distinguish between the competing explanations for Pb, and depth-profiled follow-up sampling at Site D is recommended as a priority for future work.

### 4.4. The Iron Paradox: High Concentration, Low Policy Salience

One of the most striking findings is that iron is the dominant residual contaminant by absolute concentration, reaching 1,267.3 mg/kg at Site E with a site mean of 843.2 mg/kg—the largest exceedance of the DPR TIV of any metal documented, and the only metal whose I-geo reaches Class 1 against the corrected background. Yet Fe has received substantially less attention in both policy and research relative to Pb and Zn [13]. In tropical soils, elevated Fe above 300 mg/kg exerts direct phytotoxicity through generation of reactive oxygen species [20,47] and inhibits soil microbial nitrification [48], immobilises phosphorus, suppresses organic matter accumulation, and impedes microbial community restoration. It should be noted that iron is naturally abundant in soils and its toxicity at the concentrations observed here warrants further investigation. The background level of 424.7 mg/kg used in this study derives from Onwukeme and Eze [37], the median of four southeastern-Nigeria control sites; natural Fe variability in the Bende-Ameki Formation is acknowledged, and the Fe exceedances should be interpreted alongside soil pH and redox data—measurements not available in the current study—to fully assess toxicological significance.

### 4.5. Environmental Justice and Child Health Risk

Non-carcinogenic hazard index values (Section 3.4), do not indicate elevated child health risk under the USEPA four-step framework as applied here. This does not resolve the underlying soil-quality concern: Fe, Zn, and Co concentrations remain substantially above DPR target intervention values at multiple stations (Section 3.1), and the low HI outcome reflects the specific exposure assumptions and pathway weightings of the USEPA model rather than an absence of contamination. Zinc soil ingestion is nonetheless correlated with copper deficiency and immune suppression [1,2], and cobalt accumulation via prolonged low-level exposure may be linked with thyroid disease and cardiomyopathy [3,49]. Since the sites are located close to residential areas, children could be exposed through playing on these soils, constituting a secondary dietary intake pathway [24,50,51]. This residual exposure pathway warrants continued monitoring notwithstanding the low modelled HI result. Statements regarding groundwater contamination risk are made with the caveat that no groundwater samples were collected in this study; such contamination should be treated as a potential risk requiring future monitoring rather than a confirmed outcome, and is understood to apply specifically to Site D, where Sub/Top Fe exceeds 1.0 (Section 3.2).

### 4.6. Policy Reform Requirements

Evidence from Old Nekede indicates that an environmentally effective artisan relocation programme requires at minimum four provisions absent from the current implementation model. First, a baseline soil assessment conducted before artisan departure to establish remediation targets. Second, a mandatory post-closure remediation action plan, executed within 12–24 months of departure, combining phytoremediation using *Vetiveria zizanioides* and *Chromolaena odorata* for Fe and Zn stabilisation [28,42,52], soil amendment with lime, phosphate rock, or biochar for pH adjustment and metal immobilisation [30,31,45], and topsoil capping where DPR TIV exceedances exceed a factor of five. Third, a structured time-limited monitoring programme—six-monthly soil metal and colonising vegetation assessments for a minimum of ten years—administered by the Imo State Environmental Protection Agency. Fourth, a statutory foundation through passage of a Nigerian Contaminated Land Act [34,35,53]. Whilst these findings are drawn from a single site (Old Nekede), the governance failures identified—absence of baseline data, remediation obligation, and monitoring—are consistent with documented patterns across multiple Nigerian states [8], suggesting systemic rather than site-specific deficiencies. Caution is nonetheless warranted in generalising quantitative contamination findings beyond this site.

### 4.7. Limitations

This study is subject to several limitations that should be considered when interpreting the findings. First, no pre-relocation baseline soil data exist for this site, so observations characterise post-relocation status rather than measuring a recovery trajectory against a known starting point (Section 2.1). Second, no formally designated uncontaminated control or reference site was sampled; background values are drawn from published regional literature [37] rather than a contemporaneous control (Section 2.1). Third, the five sampling stations, while stratified across the site's principal historical activity zones, cannot fully capture within-zone spatial heterogeneity across the corrected, larger site footprint of approximately 16.4 hectares (Section 2.1). Fourth, soil pH, organic carbon content, particle-size (texture), redox potential, and vegetation-recovery status were not measured, precluding direct causal attribution of the observed metal distributions to specific natural-attenuation mechanisms (Section 4.3). Fifth, no groundwater samples were collected; the assessment of downward metal migration and receptor risk therefore rests on subsoil Sub/Top ratios and inferred leaching pathways rather than on direct measurement of groundwater quality beneath the site (Sections 3.2 and 4.3). Sixth, Certified Reference Material recovery was established as a single-point check per element (Section 2.2) rather than validated across each analytical batch, and human-health risk estimates additionally rely on default USEPA absorption fractions applied to total (not bioavailable) metal concentrations; both introduce an uncertainty in measurement and exposure quantification that cannot be independently resolved with the data collected (Sections 2.4.5 and 3.4). A related gap is that cobalt oral carcinogenic risk could not be quantified, as USEPA IRIS does not publish a verified oral cancer slope factor for cobalt; cobalt risk is characterised here through the non-carcinogenic HI only (Section 2.4.5). Seventh, the study reports single composite samples per station per depth (n = 3 analytical replicates per composite only); no field replicate sampling was performed, precluding formal inter-station variability statistics for the derived contamination and risk indices beyond the reported analytical standard deviations (Sections 3.1 and 3.4). Eighth, all findings derive from a single relocated site; the extent to which these contamination and risk trajectories generalise to other artisan-relocation sites in the Niger Delta, which may differ in soil type, contaminant load, and time since relocation, remains untested. These limitations do not undermine the core source-control finding (Section 4.1) but should be weighed in any policy application of the quantitative contamination and risk estimates reported here.

## 5. Conclusions

This study conducted the first comprehensive, multi-criteria empirical assessment of artisan relocation as a soil pollution mitigation strategy in Nigeria, using the former Old Nekede mechanic village in Imo State as a case study five years post-relocation. Artisan relocation has functioned effectively as a source-control measure. The sub-detection status of Pb and Ni at all stations confirms complete cessation of new inputs of these metals, and the ecological risk index (RI = 1.0–5.5) remains within the low risk class [40]. These represent genuine, measurable policy successes.

The policy has not functioned as a complete soil pollution mitigation strategy. Fe, Zn, and Co levels continue to exceed DPR TIVs substantially; mean topsoil Fe was 843.2 mg/kg—5.6 times the TIV. PLI values of 0.17–0.76 remain below the PLI = 1.0 threshold at all five stations, indicating no net multi-metal deterioration relative to the geochemical background. Child hazard indices (HI = 0.009–0.043), do not exceed the USEPA acceptable threshold of 1.0 at any station, indicating that modelled non-carcinogenic pathway risk to children is low under the exposure assumptions applied here. This finding should be read alongside, not in place of, the TIV-exceedance results above: the site remains out of compliance with DPR soil-quality standards for Fe, Zn, and Co notwithstanding the low modelled pathway risk.

Active Fe and Zn leaching from topsoil to subsoil is confirmed at Site D specifically, with the Site D Sub/Top Fe ratio of 2.46 demonstrating that battery acid-driven downward contamination has created conditions where subsoil Fe exceeds topsoil Fe. At the remaining four stations, Sub/Top ratios below 1.0 for Fe and Zn indicate that topsoil enrichment has not yet migrated substantially downward within the five-year post-relocation window. This constitutes a potential pathway toward the shallow groundwater table at Site D—a risk that requires future groundwater monitoring to confirm. One-way ANOVA on the station composites returned significant F-statistics for Fe ($F(4,10) = 12.74$, $p < 0.001$), Zn ($F(4,10) = 8.31$, $p < 0.01$), and Co ($F(4,10) = 6.18$, $p < 0.01$); as these use analytical rather than independent field replicates (Section 4.7), they are read descriptively as evidence that station-specific reme-

diation planning is warranted, not as a formally confirmed test of spatial heterogeneity. Site D's Sub/Top Fe ratio (2.46) remains the clearest single-station evidence of active vertical transfer ($F(1,8) = 9.83$, $p < 0.01$ for the paired site-wide test; Section 3.2).

The five-year passive recovery period has produced no meaningful reduction in Fe or Zn contamination, consistent with the geochemical stability of Fe-oxide phases and Zn surface complexes in tropical sandy-loam soils and with published half-life data indicating that passive recovery would require decades to centuries [10,18]. The policy effectiveness scorecard—3 of 8 Achieved, 2 of 8 Partial, 3 of 8 Not Achieved—reflects an institutional failure characterised by the complete absence of baseline assessment, remediation obligation, or monitoring programme, notwithstanding the low modelled child-health-risk result. Five evidence-based interventions (Section 4.3) can arrest contaminant migration and protect receptor populations: soil pH management, biochar application, indigenous phytostabilisation/phytoextraction, engineered containment, and structured post-closure monitoring. Their complete absence explains contamination persistence five years post-relocation.

The immediate legislative priority is a Nigerian Contaminated Land Act mandating baseline assessment before artisan departure, mandatory post-closure remediation within 24 months, and structured long-term monitoring [34,35]. The communities surrounding Old Nekede require immediate site access controls, community health education regarding soil contact risks, and the initiation of phytoremediation trials as minimum protective measures. Whilst these findings are drawn from Old Nekede, the systemic governance failures identified are consistent across documented Nigerian artisan relocation cases; generalisation of quantitative findings requires replication at additional sites.

## Supplementary Materials

The supporting information can be downloaded at https://ojs.ukscip.com/uploads/2/asset-file/2026/09/asset-file_0a2197f05f54971b74a19a3c9e36470d.zip.

## Author Contributions

Conceptualization, sampling, and analysis of samples, I.C.H.; methodology and interpretation of data, I.C.H., C.H.N.-N., and C.C.H.; writing—original draft, I.C.H. and C.C.H.; writing—review, editing, and final approval, I.C.H., C.H.N.-N., and C.C.H. All authors have read and agreed to the published version of the manuscript.

## Funding

This research received no external funding.

## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

Data supporting the findings of this study are available within the article.

## Acknowledgments

We thank editors and reviewers for their patience, criticisms and all efforts to improve this paper and further research sincerely.

## Conflicts of Interest

The authors declare no conflict of interest.

## AI Use Statement

During the preparation of this work, the authors used Claude Sonnet 4.6, Grammarly, and QuillBot to search for relevant literature and improve the readability and language of the manuscript. All literature identified through AI-assisted search was independently verified by the authors against primary bibliographic databases before citation. All outputs were critically reviewed and edited by the authors, who take full responsibility for the integrity and accuracy of the work.

## References


1. World Health Organization. *Zinc: Environmental Health Criteria 221*; World Health Organization: Geneva, Switzerland, 2001.
2. ATSDR. *Toxicological Profile for Zinc*; US DHHS: Atlanta, GA, USA, 2005.
3. Leyssens, L.; Vinck, B.; Van Der Straeten, C.; et al. Cobalt toxicity in humans—A review of the potential sources and systemic health effects. *Toxicology* **2017**, *387*, 43–56.
4. Howard, I.C.; Abiodun, I.K. Correlation and Partitioning of Heavy Metals in Aquatic Media around a Makeshift Crude Oil Refining Area. *Int. J. Environ.* **2019**, *8*, 1–17. [CrossRef]
5. Ogbonna, P.C.; Otuu, F.C.; Okonkwo, C.J.; et al. Assessment of Heavy Metal Pollution in Soils and Plants in Mechanic Workshops in Abia State, Nigeria. *J. Appl. Sci. Environ. Manag.* **2019**, *23*, 1627–1633.
6. Ewuola, A.A.; Michael, A.B.; Sodiq, T.A.; et al. Carcinogenic and non-carcinogenic risk assessment of selected heavy metals in soil and groundwater at mechanic workshops in Ilesa, Nigeria. *GSC Adv. Res. Rev.* **2025**, *22*, 169–181. [CrossRef]
7. Uwba, S.T.; Abah, J.; Ada, C.A.; et al. Levels of Some Heavy Metals Contamination of Street Dust in the Industrial and High Traffic Density Areas of Jos Metropolis. *J. Biodivers. Environ. Sci.* **2013**, 3, 13–21. Available online: https://scholar.google.com/scholar?oi=bibs&cluster=8560781058664707701&btnI=1&hl=en
8. Nwachukwu, M.A.; Feng, H.; Achilike, K. Integrated Studies for Automobile Wastes Management in Developing Countries: In the Concept of Environmentally Friendly Mechanic Village. *Environ. Monit. Assess.* **2011**, *178*, 581–593.
9. Sam, K.; Coulon, F.; Prpich, G. Working towards an Integrated Land Contamination Management Framework for Nigeria. *Sci. Total Environ.* **2016**, *571*, 916–925. [CrossRef]
10. Kabata-Pendias, A. *Trace Elements in Soils and Plants*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2011.
11. Nathanail, J.; Bardos, P.; Nathanail, C.P. *Contaminated Land Management: Ready Reference*; Land Quality Press and EPP Publications: Nottingham/London, UK, 2002.
12. Obiora, S.C.; Chukwu, A.; Davies, T.C. Heavy Metals and Health Risk around Pb-Zn Mining in Enyigba, Nigeria. *J. Afr. Earth Sci.* **2016**, *116*, 182–189.
13. Akinola, M.O.; Njoku, K.L. Heavy Metal Contents in Soil and Plants of Auto-Mechanic Workshops, South-Western Nigeria. *Niger. J. Ecol.* **2021**, *20*, 45–58.
14. Duru, S.C.; Echiegu, E.A.; Anyadike, C.C.; et al. Spatial Variability of Heavy Metals Concentrations in Soil of Auto-Mechanic Workshop Clusters in Nsukka, Nigeria. *Sci. Rep.* **2024**, *14*, 9681. [CrossRef]
15. Elemile, O.O.; Gana, A.J.; Eijgboye, P.O.; et al. Analysis of Potentially Toxic Elements from Selected Mechanical Workshops Using the Geo-Accumulation Index and Principal Component Analysis in Omu-Aran Community, Nigeria. *Environ. Monit. Assess.* **2023**, *195*, 276. [CrossRef]
16. Müller, G. Heavy metals in the sediments of the Rhine—Changes since 1971. *Umschau* **1979**, *79*, 778–783. (in German)
17. Tomlinson, D.L.; Wilson, J.G.; Harris, C.R.; et al. Problems in Assessment of Heavy Metal Levels in Estuaries and the Formation of a Pollution Index. *Helgol. Meeresunters.* **1980**, *33*, 566–575.
18. Cornell, R.M.; Schwertmann, U. *The Iron Oxides*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2003.
19. Becker, M.; Asch, F. Iron Toxicity in Rice—Conditions and Management. *J. Plant Nutr. Soil Sci.* **2005**, *168*, 558–573.
20. Rieuwerts, J.S. The Mobility and Bioavailability of Trace Metals in Tropical Soils: A Review. *Chem. Speciat. Bioavailab.* **2007**, *19*, 75–85.
21. Adimalla, N. Heavy Metals Contamination in Urban Surface Soils of Medak Province, India, and Its Risk Assessment and Spatial Distribution. *Environ. Geochem. Health* **2020**, *42*, 59–75. [CrossRef]
22. USEPA. *Risk Assessment Guidance for Superfund*; USEPA: Washington, DC, USA, 1989.
23. USEPA. *Exposure Factors Handbook (2011 Edition)*; USEPA: Washington, DC, USA, 2011.

24. Orisakwe, O.E.; Nduka, J.K.; Amadi, C.N.; et al. Heavy Metals Health Risk Assessment for Population via Consumption of Food Crops and Fruits in Owerri, South Eastern, Nigeria. *Chem. Cent. J.* **2012**, *6*, 77. [CrossRef]
25. Adeniran, M.A.; Oladunjoye, M.A.; Doro, K.O. Soil and Groundwater Contamination by Crude Oil Spillage: A Review and Implications for Remediation Projects in Nigeria. *Front. Environ. Sci.* **2023**, *11*, 1137496. [CrossRef]
26. Ajeh, E.A.; Modi, F.J.; Omoregie, I.P. Health Risk Estimations and Geospatial Mapping of Trace Metals in Soil Samples around Automobile Mechanic Workshops in Benin City, Nigeria. *Toxicol. Rep.* **2022**, *9*, 575–587.
27. Samaila, B.; Kalgo, Z.M. Chronic Metal Overexposure in Children Due to Dietary Intake in Nigeria. *J. Pediatr. Neonatal Care* **2024**, *14*, 160–164. [CrossRef]
28. Wuana, R.A.; Okieimen, F.E. Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecol.* **2011**, *2011*, 402647.
29. Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J.L.; et al. A Review of Biochars' Potential Role in the Remediation, Revegetation and Restoration of Contaminated Soils. *Environ. Pollut.* **2011**, *159*, 3269–3282. [CrossRef]
30. Park, J.H.; Lamb, D.; Paneerselvam, P.; et al. Role of Organic Amendments on Enhanced Bioremediation of Heavy Metal(loid) Contaminated Soils. *J. Hazard. Mater.* **2011**, *185*, 549–574. [CrossRef]
31. Wang, L.; Rinklebe, J.; Tack, F.; et al. A Review of Green Remediation Strategies for Heavy Metal Contaminated Soil. *Soil Use Manag.* **2021**, *37*, 936–963.
32. Njoku, K.L.; Nwani, S.O. Phytoremediation of Heavy Metals Contaminated Soil Samples Obtained from Mechanic Workshop and Dumpsite Using *Amaranthus spinosus*. *Sci. Afr.* **2022**, *17*, e01278.
33. Department of Petroleum Resources (DPR). *Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (Revised Edition)*; DPR: Abuja, Nigeria, 2002.
34. Ogunkan, D.V. Achieving Sustainable Environmental Governance in Nigeria: A Review for Policy Consideration. *Urban Gov.* **2022**, *2*, 212–220. [CrossRef]
35. Ohanu, C.; Ibeto, C.; Ugochukwu, U. Contaminated Land Regulation in Nigeria. *J. Environ. Law* **2023**, *35*, 45–71.
36. Chikezie, I.A.; Eswaran, H.; Asawalam, D.O.; et al. Characterization of Two Benchmark Soils of Contrasting Parent Materials in Abia State, Southeastern Nigeria. *Glob. J. Pure Appl. Sci.* **2010**, *16*, 23–29. [CrossRef]
37. Onwukeme, V.I.; Eze, V.C. Identification of Heavy Metals Source within Selected Active Dumpsites in Southeastern Nigeria. *Environ. Anal. Health Toxicol.* **2021**, *36*, e2021008.
38. ISO. *Soil Quality—Extraction of Trace Elements Soluble in Aqua Regia*; International Organization for Standardization: Geneva, Switzerland, 1995.
39. Barde, B.G.; Adeleye, A.O.; Oladeji, A.A.; et al. Heavy Metals Pollution and Ecological Risk Assessment around Artisanal Gold Mines in Zamfara, Nigeria. *Environ. Anal. Health Toxicol.* **2024**, *39*, e2024016.
40. Hakanson, L. An Ecological Risk Index for Aquatic Pollution Control. *Water Res.* **1980**, *14*, 975–1001.
41. USEPA. *Regional Screening Level (RSL)*; USEPA: Washington, DC, USA, 2024. Available online: https://www.epa.gov/risk/regional-screening-levels-rsls
42. Bankole, A.; Ogunkeyede, A.; Ngo, H.; et al. Ecological Risks of Heavy Metals Found in Soils at Informal E-Waste Processing Sites in Nigeria. *Eur. J. Sci. Innov. Technol.* **2024**, *4*, 417–434.
43. Shaheen, S.M.; Antoniadis, V.; Kwon, E.; et al. Soil Contamination by Potentially Toxic Elements and the Associated Human Health Risk in Geo- and Anthropogenic Contaminated Soils: A Case Study from the Temperate Region (Germany) and the Arid Region (Egypt). *Environ. Pollut.* **2020**, *262*, 114312. [CrossRef]
44. Adriano, D.C. *Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability, and Risks of Metals*, 2nd ed.; Springer: New York, NY, USA, 2001.
45. El-Naggar, A.; Shaheen, S.M.; Hseu, Z.Y.; et al. Biochar Affects the Dissolved and Colloidal Concentrations of Cd, Cu, Ni, and Zn and Their Phytoavailability and Potential Mobility in a Mining Soil under Dynamic Redox Conditions. *Sci. Total Environ*. **2018**, *624*, 1059–1071. [CrossRef]
46. Narayanan, M.; Ma, Y. Influences of Biochar on Bioremediation/Phytoremediation Potential of Metal-Contaminated Soils. *Front. Microbiol.* **2022**, *13*, 929730. [CrossRef]
47. Majerus, V.; Bertin, P.; Swenden, V.; et al. Organ-Dependent Responses of the African Rice to Short-Term Iron Toxicity: Ferritin Regulation and Antioxidative Responses. *Biol. Plant.* **2007**, *51*, 303–312. [CrossRef]
48. Rabêlo, F.H.S.; Vangronsveld, J.; Baker, A.J.M.; et al. Are Grasses Really Useful for the Phytoremediation of Potentially Toxic Trace Elements? A Review. *Front. Plant Sci.* **2021**, *12*, 778275. [CrossRef]
49. Ijomone, O.M.; Ifenatuoha, C.W.; Aluko, O.M.; et al. The Aging Brain: Impact of Heavy Metal Neurotoxicity. *Crit. Rev. Toxicol.* **2020**, *50*, 801–814. [CrossRef]
50. Iwegbue, C.M.; Nnanna, C.A.; Ogwu, I.F.; et al. Concentrations, Sources and Exposure to Metals in Dust from Automobile Mechanic Workshops in Nigeria. *J. Trace Elem. Miner.* **2024**, *10*, 100186.

51. Nduka, J.K.; Umeh, T.C.; Kelle, H.I.; et al. Ecological Pollution Features and Health Risk Exposure to Heavy Metals via Street Dust and Topsoil from Nkpor and Onitsha in Anambra, Nigeria. *Environ. Anal. Health Toxicol.* **2024**, *39*, e2024005.
52. Ali, H.; Khan, E.; Ilahi, I. Environmental Chemistry and Ecotoxicology of Hazardous Heavy Metals: Environmental Persistence, Toxicity, and Bioaccumulation. *J. Chem.* **2019**, *2019*, 6730305. [CrossRef]
53. Sam, K.; Zabbey, N.; Onyena, A.P. Implementing Contaminated Land Remediation in Nigeria: Insights from the Ogoni Remediation Project. *Land Use Policy* **2022**, *115*, 106051.

Copyright © 2025 by the author(s). Published by UK Scientific Publishing Limited. This is an open access article under the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Publisher's Note: The views, opinions, and information presented in all publications are the sole responsibility of the respective authors and contributors, and do not necessarily reflect the views of UK Scientific Publishing Limited and/or its editors. UK Scientific Publishing Limited and/or its editors hereby disclaim any liability for any harm or damage to individuals or property arising from the implementation of ideas, methods, instructions, or products mentioned in the content.