

Research Article

Natural Attenuation of Heavy Metals and Explosive Residues at Military Demolition Sites in Agrarian Ecosystems

Gregory Odimgbe^{*} , Olukayode Akinyemi, Babatunde Saheed Bada, Amidu Olalekan Mustapha

Environmental Systems and Climate Change, Federal University of Agriculture Abeokuta, Abeokuta, Nigeria

Abstract

This study investigated the natural attenuation of heavy metals and explosive residues resulting from military ammunition demolition activities in agrarian ecosystems of Nigeria, with Alamala serving as the primary focus. It examined the environmental and health risks associated with both historical and current disposal practices, evaluating the persistence and reduction of contaminants such as RDX, TNT, HMX, perchlorate, and various heavy metals. Seasonal and spatio-temporal sampling was conducted across soil, water, air, and vegetation in the demolition zones and surrounding communities. Samples were analysed for physicochemical parameters including pH, BOD, COD, TDS, and metal concentrations. The results revealed consistent patterns in iron and zinc levels, notable fluctuations in copper, and elevated concentrations of lead, particularly at the Alamala site. Seasonal variations influenced contaminant migration, with chloride and sulphate dominating the water chemistry. Explosive residues and heavy metals showed distinct attenuation behaviours across environmental compartments. Over a 90-day post demolition period, contaminant concentrations changed at varying rates, reflecting the natural remediation processes occurring in soil, water, and plants. Statistical analyses, including time series and regression models, identified compartment-specific attenuation rates and highlighted the complex interactions between environmental factors and contaminant behaviour. The study provided critical insights into the ecological impacts of demolition activities, contributing to informed risk assessment and environmental policy development in militarized agrarian regions.

Keywords

Natural Attenuation, Heavy Metals, Explosive Residues (RDX, TNT, HMX, Perchlorate), Military Ammunition Demolition, Spatio-temporal Analysis, Environmental Compartments

1. Introduction

Military activities, particularly the disposal of obsolete or surplus munitions, had long been recognized as significant contributors to environmental pollution. In many low and middle income countries, including Nigeria, the accumulation

of heavy metals and energetic chemical residues in soil, water bodies, and vegetation emerged as a growing environmental and public health concern [1, 2]. These contaminants originated from various operations, including ammunition

^{*}Corresponding author: odimgregarmy@gmail.com (Gregory Odimgbe)

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production, testing, storage, and demolition, especially through open detonation or burning.

In Nigeria, open-field demolition remained the dominant practice for disposing of expired munitions. While operationally simple and cost-effective, this method often introduced toxic xenobiotic compounds into agrarian ecosystems. Explosive residues such as trinitrotoluene (TNT), Royal Demolition Explosive (RDX), and octogen (HMX)

were known for their chemical stability and persistence in the environment. They posed ecological and health risks due to their toxicity and carcinogenic potential [3, 4]. These substances accumulated in soils and water, disrupted microbial communities, impaired plant growth, and were capable of entering food chains through bioaccumulation [5, 6].



Figure 1. Ammunition Set Aside for Demolition.

Ammunition Set Aside for Demolition

Source: Photographs from Ammunition set aside for demolition.

A notable example occurred during the 2016 “Exercise Ground Thunder” in Alamala, Ogun State, where the Nigerian Army demolished obsolete naval munitions, including Sea Cat and Ottomat missiles, grenades, torpedoes, and plastic explosives [1]. The operation discharged significant quantities of energetic residues and heavy metals into the environment. Despite the scale of the event, no formal environmental remediation was undertaken. After the exercise, the site was closed off, however, agricultural activities quickly resumed in the absence of environmental monitoring or remediation efforts. This situation mirrors a wider national pattern, where more than ten major demolition sites and numerous firing ranges have operated with little to no regulatory oversight.

Contaminants from such sites did not remain confined to their points of release. Through surface runoff, leaching, and atmospheric dispersion, pollutants migrated to surrounding areas, infiltrating groundwater and affecting surface waters, farmlands, and communities [2, 3]. Long-term exposure to these compounds had been linked to adverse outcomes such as neurotoxicity, endocrine disruption, thyroid dysfunction, and cancer [4, 5]. However, empirical data on the persistence and environmental fate of these contaminants in Nigeria, especially under tropical conditions, remained limited.

Given the high cost and limited feasibility of engineered remediation methods, such as soil excavation or chemical treatment, natural attenuation had been considered a potentially viable alternative. This passive remediation process involved the gradual reduction of contaminant concentrations through natural mechanisms, including volatilization, dilution, sorption, microbial degradation, and abiotic transformation [6, 7]. However, the success of such processes depended on environmental factors like soil properties, rainfall patterns, and microbial activity, all of which varied with season and location.

This study therefore assessed the natural attenuation of heavy metals and explosive residues in the post-demolition landscape of Nigerian military sites, with Alamala serving as the impacted site and Odogbo as a control. It examined the seasonal and spatial distribution of contaminants across soil, water, and plant compartments, quantified changes in concentration over time, and identified physicochemical drivers influencing remediation. The findings contributed to improved environmental risk assessments, policy development, and sustainable land-use planning in militarized agricultural zones.

2. Materials and Methods

2.1. Study Sites

This study was conducted at the Alamala military demolition site in Abeokuta, Ogun State, Nigeria, with the Odogbo demolition site in Ibadan, Oyo State, serving as a control. Alamala (7°11'N, 3°14'E) is an active demolition range located along the Lagos-Sokoto Expressway within Abeokuta North Local Government Area, covering approximately 2,703,744.48 m². The region lies within a tropical agro-ecological zone characterized by distinct wet and dry seasons, moderate elevation, and mixed vegetation of rainforest and wooded savanna. The soils are primarily lateritic and derived from deeply weathered parent materials, rich in iron and aluminium oxides, and generally suitable for plantation farming, including rubber, cocoa, and oil palm.

Odogbo (7°25'N, 3°59'E), located in Ibadan, served as a comparative control due to its abandonment since 1995 following civilian encroachment. The site was previously active from 1985 to 2003. It shares similar climatic and ecological conditions with Alamala but lacks recent explosive activity, making it a suitable reference for background contaminant levels. Odogbo is situated at a higher elevation (273 m) than Alamala (145 m), with denser surrounding population. The contrasting site histories and ecological contexts provided a robust framework for assessing natural attenuation processes in post-demolition agrarian environments.

2.2. Study Design

This study employed a stratified, comparative design to evaluate the spatio-temporal and seasonal dynamics of environmental contaminants at the Alamala demolition site (active) and Odogbo site (decommissioned) in southwestern Nigeria. Sampling was conducted across two consecutive years (2020-2021), covering both the wet season (April-October) and dry season (November-March). A total of four environmental compartments soil, water (surface and groundwater), vegetation, and air were monitored. Sampling points were established at three radial distances (50 m, 100 m, and 200 m) from the blast epicentre to capture contaminant dispersion gradients. Odogbo, which has been inactive since 1995, served as a control site for baseline comparison. Samples were also collected monthly following demolition events at Alamala to assess attenuation trends over time.

2.3. Sample Collection

Representative environmental samples, soil, surface and underground water, vegetation, and air, were collected systematically from the Alamala demolition site, nearby communities, and the Odogbo control site. Soil samples (0-15 cm depth) were obtained using a stainless, steel auger,

air-dried, sieved to 2 mm, and stored in labelled polyethylene bags. Water samples from boreholes and surface sources were collected in acid-washed bottles, filtered using 0.45 µm membrane filters, and acidified to pH <2 with nitric acid (HNO₃) to prevent metal precipitation. Dominant grass species were clipped 5 cm above ground level, rinsed with distilled water, oven-dried at 65 °C, ground, and stored in airtight containers. Air samples were collected twice daily using high-volume samplers (1.13 m³/min) fitted with glass fibre filters over 24 hour periods. Sampling was conducted monthly across the 2020 rainy season and the 2020/2021 dry season, with intensified post demolition collections between May and August 2021. GPS coordinates and meteorological data were recorded at all sampling points.

Odogbo was chosen as the control due to its long decommissioning, civilian encroachment, and absence of recent demolitions, enabling natural recovery. Sharing similar climate, soil, and land-use with Alamala but differing in disturbance history, it isolates demolition effects. Baseline sampling and acceptance criteria (explosive detection, metal levels, multivariate tests) verified Odogbo's suitability as a reference site.

Table 1. The Coordinates and Altitude of the Principal Study Site.

Serial Number	Coordinates	Altitude	Remarks
1.	Lat. 07°12'314" Long-003°14'707"	35.5m	AP1, AS1
2.	Lat- 07°12'363" Long-003°14'678"	28.5m	AP2, AS2
3.	Lat-N 07°12'353" Long-003°14'575"	48.1m	AP3, AS3

Table 2. The Coordinates of the Immediate Community to the Principal Demolition Site.

Serial Number	Coordinates	Topography	Remarks
1.	Lat. 07°12'690" Long-003°14'578"	65.5M	AP4, AS4, AW1
2.	Lat. 07°12'600" Long-003°14'750"	56.6M	AP5, AS5, AW2
3.	Lat. 07°11'630" Long-003°14'341"	75.7M	AP6, AS6, AW3

AP=Plant Sample
AS=Soil Sample
AW= Water Sample

2.4. Analytical Procedures

All environmental samples were subjected to both qualitative and quantitative analyses to detect the presence and concentration of heavy metals, explosive residues, and key physicochemical parameters. Physicochemical properties, pH, COD, BOD, TDS, and EC, were determined using APHA standard methods. Heavy metals (Pb, Ni, Cd, Hg, Zn, Fe, Cu, Mn, Cr, As) were extracted via acid digestion with $\text{HNO}_3/\text{HClO}_4$ and analysed using Atomic Absorption Spectrophotometry (PerkinElmer A Analyst 400). Explosive residues including TNT, 2,4-DNT, and RDX were extracted from soil with acetone and analysed using both field colorimetric techniques and laboratory-based Gas Chromatography-Mass Spectrometry (Agilent 7890A/5975C). Absorbances at 540 nm (TNT), 570 nm (DNT), and 507 nm (RDX) were recorded. Air samples were screened for CO, NO_x, SO₂, and NH₃ using portable ambient samplers. Quality assurance included blanks, replicates, and certified reference materials. Contaminant decay was estimated by comparing May and July 2021 values using an exponential decay model to quantify attenuation rates in affected matrices.

AAS: Calibration curves for Pb, Zn, Cu, Cd, Cr, and Fe were constructed using certified multi-element standards (Merck, Germany) over 0.01-10.0 mg/L with correlation coefficients ($R^2 > 0.995$). Method detection limits (MDLs) ranged from 0.002-0.010 mg/L in water and 0.05-0.20 mg/kg in soils/plants, depending on the element. Precision and accuracy were verified by triplicate analysis of procedural blanks and certified reference materials (CRM 7001 Light Sandy Soil, IAEA-Vegetation). Mean recoveries were 92-105% across all metals, with relative standard deviations (RSDs) <5%.

GC-MS: Energetic compounds (RDX, TNT, HMX, and DNTs) were quantified using an Agilent 7890A GC coupled to a 5975C MS. Calibration curves were prepared with analytical standards (Supelco, USA) spanning 0.01-5.0 mg/L ($R^2 > 0.996$). MDLs were 0.001-0.005 mg/L in water and 0.01-0.05 mg/kg in soils/plants. Surrogate standards (nitrobenzene-d5) were added to all samples to track recovery. Mean recoveries ranged 88-110%, with RSDs <7%. Laboratory blanks and matrix spikes were run at 10% frequency; no target analytes were detected in blanks.

2.5. Data Analysis

Data were analyzed using a combination of descriptive and inferential statistical techniques to assess contaminant dynamics across seasons, matrices, and sites. Mean concentrations were calculated, and differences between

contaminants and across months were tested using Time-series and regression analyses to model contaminant attenuation over time.

At each site and for each sampling campaign, we collected triplicate (n=3) samples per matrix (soil, water, vegetation, air) at each radial distance (50, 100, 200 m) in both seasons (wet: Apr-Oct; dry: Nov-Mar), yielding n=3 per matrix × distance × month.

Table 3. Sampling Procedure.

Matrix	Distances from blast center	Replicates per distance (per month)	Seasons covered
Soil	50, 100, 200 m	n=3	Wet & Dry
Water	50, 100, 200 m	n=3	Wet & Dry
Vegetation	50, 100, 200 m	n=3	Wet & Dry
Air	50, 100, 200 m	n=3 (filters)	Wet & Dry

$$X = \frac{(C_2 - C_1)}{C_1} \times 100$$

Where:

X = percentage difference

C1 = initial concentration (May 2021)

C2= concentration in subsequent months

The natural attenuation of contaminants was further evaluated using the exponential decay model:

$$y = A_0 e^{-kt}$$

and

$$X = \frac{(Y - A_0)}{A_0} \times 100$$

Where:

y= concentration at time ttt (e.g., July 2021)

A0 = initial concentration (May 2021)

k= decay constant (remediation rate)

t= time interval (90 days)

3. Results and Discussion

Ambient Air Quality Concentrations

Table 4. Comparison of Physicochemical properties against Established Standards.

Parameter	Alamala Mean $\pm$ SD ($\mu\text{g}/\text{m}^3$)	Odogbo Mean $\pm$ SD ($\mu\text{g}/\text{m}^3$)	WHO/USEPA Guideline ($\mu\text{g}/\text{m}^3$)	Remark
PM _{2.5}	58.3 $\pm$ 12.1	24.7 $\pm$ 6.5	15 (24-h avg, WHO)	Alamala exceeds guideline
PM ₁₀	103.4 $\pm$ 18.7	49.2 $\pm$ 10.4	45 (24-h avg, WHO)	Alamala exceeds guideline
NO ₂	48.5 $\pm$ 9.2	21.6 $\pm$ 5.3	25 (annual mean, WHO)	Alamala higher
SO ₂	22.7 $\pm$ 4.1	12.3 $\pm$ 3.0	20 (24-h avg, WHO)	Within range
CO	5.2 $\pm$ 1.0 (ppm)	2.3 $\pm$ 0.7 (ppm)	4 (24-h avg, WHO)	Slightly elevated at Alamala
RDX (vapor/particulate)	0.014 $\pm$ 0.005	<LOD	No standard	Detected only at Alamala
TNT (vapor/particulate)	0.009 $\pm$ 0.003	<LOD	No standard	Detected only at Alamala

3.1. Heavy Metal Contamination

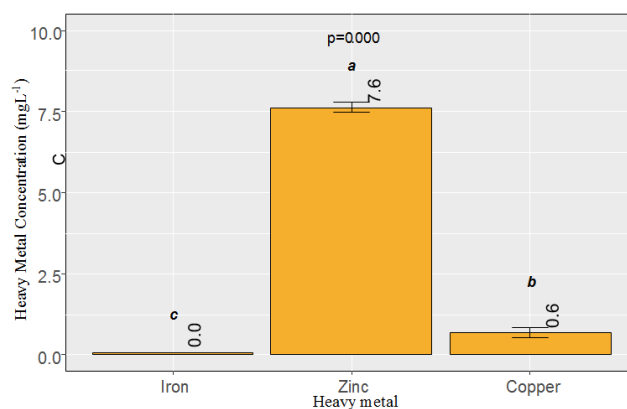
Heavy metal analysis revealed significant spatial and temporal variations across soil, water, and plant samples. Zinc was the most abundant metal in water (mean 7.65 mg/L), followed by copper and iron, though no significant remediation was observed for Fe and Zn during the 90-day post-demolition period. Soil samples showed elevated levels of Fe (85.6 mg/L), Zn (79.61 mg/L), and Cu (4.72 mg/L), with Pb exhibiting modest natural attenuation, faster in community areas (0.88%) than at the demolition site (0.33%). Cr and Cd declined slightly pre-demolition but remained unchanged afterward. In plants, Pb levels dropped more in the community (60%) than at the site (30%), while Fe, Zn, and Cu remained stable. Statistical analysis confirmed that location significantly influenced concentrations of Fe, Ni, and Cd in both soil and vegetation ($P < 0.05$). Overall, natural attenuation was limited, with most metals showing persistence in environmental compartments, especially at the demolition site, highlighting long-term ecological risks.

Table 5. Mean Monthly Heavy Metal Concentration in Water at The Demolition Site.

Month	Iron	Zinc	Copper
Nov_20	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.63 $\pm$ 0.5
Dec_20	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.63 $\pm$ 0.5
Jan_21	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.63 $\pm$ 0.5
Feb_21	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.63 $\pm$ 0.5
Apr_21	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.63 $\pm$ 0.5
May_21	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.77 $\pm$ 0.57

Month	Iron	Zinc	Copper
Jun_21	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.77 $\pm$ 0.57
Jul_21	0.06 $\pm$ 0.01	7.62 $\pm$ 0.52	0.77 $\pm$ 0.57
P-value	1.000	1.000	1.000

Mean values in columns do not differ significantly ($P > 0.05$) (Mn, As, Hg and Pb were not detected).

**Figure 2.** Mean Heavy Metal Concentration in Water from the Demolition Site (Mean values on bars with different letters of the alphabet differ significantly, ANOVA: $p < 0.05$).

3.2. Explosive Residues

Explosive residues, TNT, DNT, and RDX, were detected in soil and plants from both the demolition site and surrounding community, with notable spatial and temporal trends. TNT levels in soil increased post-demolition, particularly at the site, peaking at 55.88% above May 2021 levels in June. In plants, TNT and DNT concentrations were consistently higher at the

demolition site before and after the event, but remediation occurred more rapidly in the surrounding community. The rate of decay for TNT in soil was 0.49%/day at the site compared to 0.05%/day in the community. RDX showed the highest remediation, with a decay rate of 0.81%/day in site soil and 0.27%/day in community plants. DNT levels in the community declined faster in both soil (0.37%/day) and plants (0.29%/day) than at the site. Overall, while explosive residues declined modestly, natural attenuation was more effective in community vegetation than in demolition site soils, suggesting differential degradation influenced by environmental and microbial factors.

Table 6. Mean Concentration of Explosive in Soil and Plants from the Demolition Site and Surrounding Community.

Location	TNT	DNT	RDX
Sample source: Soil			
Community	0.36 ± 0.04	0.46 ± 0.05	0.61 ± 0.07 ^b
Site	0.54 ± 0.08	0.42 ± 0.05	1.32 ± 0.32 ^a
P-value	0.165	0.558	0.052
Sample source: Plant			
Community	32.45 ± 4.94 ^b	44.88 ± 7.94 ^b	51.16 ± 9.67 ^b
Site	2186.52 ± 514 ^a	3868.06 ± 921 ^a	1380.16 ± 312 ^a
P-value	0.000	0.000	0.001

Means of explosive concentrations in the same column of sample source followed by different superscripts differ significantly ($P < 0.05$).

3.3. Physicochemical Variability

The physicochemical properties of soil and water across the demolition site and surrounding agrarian community displayed significant temporal and spatial variability, affecting contaminant mobility and natural attenuation. Parameters such as pH, electrical conductivity, and total organic carbon fluctuated with seasonal patterns, especially during and after demolition activities. Soil pH ranged from slightly acidic to neutral, which may have enhanced the mobility of certain metals like Zn and Cu, while inhibiting their natural remediation. Elevated EC values, especially at the demolition site, indicated increased ionic content, likely due to the deposition of explosive and metal residues. TOC

was generally higher in the surrounding community, potentially facilitating microbial degradation of explosive residues such as TNT and DNT. Water samples showed higher turbidity and EC immediately after demolition, reflecting contaminant leaching. These physicochemical trends suggest that local environmental conditions, particularly soil organic content and Ph, play a critical role in the fate and natural attenuation of both heavy metals and energetic compounds, with better remediation outcomes observed in the biologically active surrounding community soils.

3.4. Spatial and Seasonal Influence

Spatial and seasonal variations significantly influenced the concentration and attenuation of contaminants across the demolition site and surrounding agrarian environments. Contaminant levels were generally higher at the demolition site compared to the surrounding community, reflecting localized deposition. However, natural remediation rates were consistently faster in the community, attributed to greater vegetation cover and biological activity. Seasonal trends showed that the dry season (e.g., November-February) recorded higher accumulation of metals and explosives, while the early rainy season (June-July) saw limited or no remediation in most compartments. For instance, lead and chromium showed measurable reductions in soil and plant tissues during transition months, while other metals like Cu and Zn exhibited persistence. Explosive residues such as TNT and RDX also declined more rapidly in community soils and plants, particularly in pre-demolition months. These trends affirm the importance of both location and season in influencing natural attenuation.

3.5. Attenuation Rates

The attenuation rates of contaminants varied significantly between the demolition site and the surrounding community. Lead (Pb) in soil showed higher remediation in the community (0.00987%/day) than at the site (0.00365%/day), with plant uptake also favouring the community (0.0288%/day). Chromium (Cr) was the only heavy metal with notable decay in soil, higher at the site (0.145%/day). Explosives like RDX decayed faster in soil at the demolition site (0.8121%/day), while plant-based remediation was more effective in the community (0.269%/day). TNT and DNT also followed this trend, with rapid decline in plant tissues from the surrounding community compared to the demolition site. No remediation was observed for Fe, Zn, Cu, Mn, Ni, and Cd in either soil or plants over the 90-day monitoring period.

Table 7. Rate of decay (%.day) of the contaminants in the soil and plants over 90 days.

Location	Pb	Fe	Zn	Cu	Mn	Ni	Cr	Cd
	Soil							
Community	-0.00987	0	0	0	0	0	-0.11456	0
Site	-0.00365	0	0	0	0	0	-0.1447	0
	Plants							
Community	-0.028816	0	0	0	0	0	0	0
Site	-0.004049	0	0	0	0	0	0	0

Table 8. Rate of decay (%.day⁻¹) of the explosives in the soil and plants over 90 days.

	TNT	DNT	RDX
	Soil		
Community	-0.04536	-0.36694	-0.29807
Site	-0.49326	-0.34165	-0.8121
	Plants		
Community	-0.25016	-0.29036	-0.26945
Site	-0.03515	-0.09809	-0.08238

Comparison with Guideline Values and Health Risk Implications

The concentrations of selected metals and explosive residues at the Alamala demolition site were compared with World Health Organization (WHO), Food and Agriculture Organization (FAO), Codex Alimentarius, and national guideline values to assess potential risks to human health.

Metals in water. Zinc concentrations in Alamala water averaged 7.62 mg/L, exceeding the WHO taste/acceptability threshold of 3 mg/L and the U.S. EPA secondary standard of 5 mg/L [1, 2]. This indicates that the water is unsuitable for direct consumption and may cause gastrointestinal disturbances and long-term effects on copper metabolism. Copper levels (0.63-0.77 mg/L) were below the WHO guideline value of 2 mg/L and the U.S. EPA action level of 1.3 mg/L [1, 2], suggesting minimal immediate risk, although periodic monitoring is advisable. Iron concentrations (0.06 mg/L) were well below the aesthetic guideline of 0.3 mg/L [1], with no significant health concern. Lead was not detected in water, meeting the WHO guideline of 0.01 mg/L [1].

Metals in plants. Plant tissue Pb concentrations (mean $\approx$ 0.26 mg/kg) approached or exceeded Codex maximum levels for vegetables (0.1-0.3 mg/kg) [3]. Chronic dietary exposure to Pb, even at low levels, poses serious risks, particularly neurodevelopmental impairment in children, underscoring the

absence of a safe threshold [4].

Explosives in soils and plants. TNT, RDX, and DNT were detected in Alamala soils and plant tissues at substantially elevated levels (e.g., TNT in plants $\approx$ 2186 mg/kg; soil TNT $\approx$ 0.54 mg/kg). While no WHO or FAO guideline values exist for energetic compounds, U.S. EPA and ATSDR identify RDX and TNT as toxic substances linked to hepatic, renal, and neurological effects, with TNT additionally considered genotoxic and potentially carcinogenic [2, 5, 6]. The presence of such residues in edible plants indicates a significant pathway for human exposure.

Health-risk implications. Drinking-water pathway: Elevated Zn renders Alamala water unsuitable for consumption without treatment. Cu and Fe concentrations are within acceptable limits, but monitoring is necessary to track possible fluctuations. The absence of Pb is reassuring, though continued surveillance is warranted given its high toxicity.

Dietary pathway: Uptake of Pb and explosives by crops presents the most critical risk, as consumption of contaminated produce could result in severe chronic health outcomes, including neurotoxicity, organ damage, and potential carcinogenicity. Restricting agricultural use of contaminated areas and testing local produce are essential precautionary steps.

Soil and inhalation pathway: Contaminated soils and resuspended dust particles represent additional exposure routes, particularly for children. The co-occurrence of metals and energetic residues in airborne particulates, combined with elevated PM_{2.5} and PM₁₀ levels, amplifies inhalation risks for surrounding communities.

4. Conclusion

This study underscored the persistence and complex dynamics of heavy metals and explosive residues at Nigerian military demolition sites, particularly in agrarian ecosystems. The Alamala site exhibited significant contamination, with elevated levels of lead, zinc, copper, and explosive compounds such as TNT and RDX detected in soil, water, and vegetation. Although some degree of natural attenuation occurred, especially in the surrounding community, most contaminants persisted over the 90-day post-demolition period, indicating potential long-term ecological and health risks.

Natural remediation was influenced by spatial and seasonal factors. Contaminant decay rates were consistently higher in the community compared to the demolition site, likely due to greater vegetation cover, higher organic matter content, and enhanced microbial activity. Seasonal variability also affected contaminant behaviour, with the dry season favouring accumulation and the rainy season promoting dispersal, though not always degradation. Physicochemical parameters such as pH, electrical conductivity, and total organic carbon played critical roles in mediating these processes by influencing contaminant mobility and bioavailability.

The findings revealed the limitations of relying solely on natural attenuation in heavily impacted zones like Alamala, where certain metals and residues remained largely unchanged. While community environments showed more favourable conditions for passive remediation, the persistence of contaminants like iron, cadmium, and TNT suggested that supplemental management strategies were necessary. Overall, the research provided valuable insights into the environmental consequences of open-field ammunition disposal and supported the development of informed remediation policies and sustainable land-use planning in militarized agrarian settings.

5. Recommendations

Based on the findings, it is recommended that regular environmental monitoring be established at military demolition sites to track contaminant levels over time. Engineered remediation methods, such as phytoremediation and soil amendments, should complement natural attenuation, especially in heavily contaminated zones like Alamala. Policies must enforce stricter controls on ammunition disposal practices to minimize environmental release of

hazardous substances. Community awareness programs should be implemented to educate local populations on potential risks. Further research is needed to explore microbial and biochemical mechanisms driving contaminant degradation under tropical conditions, enhancing the effectiveness of sustainable remediation strategies in Nigerian agrarian ecosystems.

Abbreviations

PHA	American Public Health Association
ATSDR	Agency for Toxic Substances and Disease Registry
AWWA	American Water Works Association
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DNT	Dinitrotoluene
EC	Electrical Conductivity
GC-MS	Gas Chromatography-Mass Spectrometry
HSDB	Hazardous Substances Data Bank
HMX	Octogen (High Melting Explosive)
mg/L	Milligrams per Litre
Ni	Nickel
Pb	Lead
RDX	Royal Demolition Explosive (Cyclotrimethylenetrinitramine)
TDS	Total Dissolved Solids
TNT	Trinitrotoluene
TOC	Total Organic Carbon
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

Conflicts of Interest

The authors declare that they have no known financial or personal relationships that could have appeared to influence the work reported in this paper.

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