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Spatial Distribution and Environmental Risk of Explosive Residues (TNT, and DNT Isomers) in Soils and Surface Waters of Gwoza LGA, North-East Nigeria

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Abstract.

Objective:

Quantify and interpret concentrations of explosives residues in soils and surface waters of five sampling points SP1-SP5 of Boko Haram/Military detonation sites in Gwoza LGA and assess spatial differences using a one-way ANOVA in triplicate measurements mean±SD. Methods: For soils and sample waters, nitroaromatics TNT, DNB, TNB, 2,4-DNT, 2,6-DNT, NP, NT and nitramines RDX, HMX were shown as mean±SD (mg/kg) and (mg/L). We calculated ANOVA from summary statistics to compare differences among sampling points in each compound and matrix of which we reported effect sizes. Soils' concentrations were one to three orders of magnitude higher than water's, as a byproduct of strong sorption. Hotspots were found in SP4 for 2,6-DNT and 2,4-DNT and in SP2–SP3 for TNT . Several soil analytes revealed significant spatial heterogeneity according to ANOVA, and "notably TNT, 2,4-DNT, 2,6-DNT" had a large effect ($\eta^2 = 0.8$). The result is that Patterns "reflect the proximity to detonation/handling areas, soil organic matter mediated sorption, and the transformation of 2,4,6-TNT to DNT
isomers, whereas aqueous concentrations remain low due to the dilution and photolysis". As a consequence, the findings qualify for a targeted risk assessment and erosion/storm-water controls at hotspot

Introduction

1.1 Background to the Study

Armed conflicts and insurgencies are often associated with long-lasting environmental consequences that extend far beyond immediate human and infrastructural damage. One major but less visible legacy of conflict is the contamination of soils and water bodies with explosive residues. During detonation events, misfires, or improper handling of munitions, energetic compounds are released into the environment. These substances, including nitroaromatics such as 2,4-dinitrotoluene (2,4-DNT),2,6-dinitrotoluene(2,6-DNT), trinitrotoluene (TNT), dinitrobenzene (DNB), and trinitrobenzene (TNB), as well asnitraminessuchascyclotrimethylenetrinitramine (RDX) and octogen (HMX), are of global environmental concern.

The environmental impact of explosive remnants of war (ERW), like landmines and unexploded ordnance, is a significant concern due to their persistence, low biodegradability, and high toxicity. These materials are not just hazards on the battlefield; they contaminate soil and groundwater and can accumulate in plants and aquatic life, posing serious risks to ecosystems and human health. Research from Europe, the United States, and Asia has shown that substances like TNT, RDX, HMX, and pentaerythritol tetranitrate (PETN) are often

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found in areas that have experienced military activities. The contamination varies in concentration, with higher levels typically located around explosion sites and former battlegrounds. Their persistence, low biodegradability, and high toxicity have been widely documented (USEPA, 2012; Jenkins *et al*., 2006).

Globally, explosive remnants of war (ERW), including landmines, unexploded ordnance, and residues from detonation events, are recognized as significant environmental pollutants. These contaminants not only persist in soils and groundwater but can also bioaccumulate in plants and aquatic systems, posing risks to both ecological integrity and human health. Previous studies in Europe, the United States, and Asia have shown that TNT, RDX, HMX, and pentaerythritol tetranitrate (PETN) are frequently detected in areas with a history of military activity (Zhang *et al.*, 2020). Such contamination is often spatially heterogeneous, with higher concentrations around explosion craters and former battlegrounds.

Nigeria's North-East has been the center of the Boko Haram insurgency since 2009, bringing significant turmoil to the region. The group's frequent use of improvised explosive devices (IEDs), coupled with military operations, has left a lasting impact on the landscape, creating numerous craters and leaving behind unexploded devices that disrupt the environment. Among the areas severely impacted, Borno State stands out, particularly Gwoza Local Government Area (LGA), which has been one of the worst-affected regions.

Gwoza’s semi-arid landscape, with its limited surface water and fragile soils, is especially vulnerable to contamination. The explosive remnants can seep into the soil, potentially leaching into the groundwater and lingering for long periods due to the low microbial activity in the area. This situation poses serious risks, as communities may be exposed to these hazardous materials through drinking water, irrigation, and farming practices.

The ongoing social and humanitarian crises caused by the conflict have overshadowed any environmental monitoring efforts, creating significant gaps in our understanding of how explosive residues are affecting the region. While globally the dangers posed by explosives are well recognized, there is surprisingly little information available regarding their impact in conflict-affected areas of sub-Saharan Africa.

In Gwoza, repeated detonation events have likely released considerable amounts of toxic compounds such as TNT, RDX, and HMX into the soil and nearby water systems. These substances have been linked to various health risks, including toxicity, genetic mutations, and potential cancer development. They can inhibit soil microbial activity and contaminate groundwater, posing long-term health hazards to local communities.

Despite the urgent need for information, there is a lack of scientific research focused on the environmental distribution of these explosive residues in Nigeria's North-East. No comprehensive study has yet measured the levels of TNT, RDX, and HMX in Gwoza’s soil and water, nor have the potential risks to human and environmental health been properly evaluated. Without this critical data, it is challenging to devise effective remediation strategies or informed policy responses. Nigeria’s North-East has been at the epicenter of the Boko Haram insurgency since 2009. The group’s extensive use of improvised explosive devices (IEDs), combined with military counteroffensives involving conventional munitions, has left behind numerous craters, unexploded devices, and widespread environmental disturbance. Borno State, in particular, has been severely affected, with Gwoza Local Government Area (LGA) emerging as one of the hardest-hit regions. Gwoza’s semi-arid environment, characterized by limited surface water and fragile soils, is particularly vulnerable to contamination. Explosive residues in such settings can infiltrate soil pores, leach into groundwater, and persist for extended periods due to low microbial activity and poor natural attenuation. This creates a potential pathway for human exposure through drinking water, irrigation, and agricultural practices. The social and humanitarian crises triggered by conflict have overshadowed environmental monitoring, leaving significant data gaps on the fate and distribution of explosive residues in the region (Theresa *et al.*, 2022). While the health and ecological risks of explosives are well established globally, very little is known about their occurrence and impacts in conflict-affected regions of sub-Saharan Africa. In Gwoza, repeated detonation events have likely deposited substantial amounts of TNT, RDX, and HMX into soils and adjacent water systems. These compounds are toxic, mutagenic, and potentially carcinogenic, with reported effects ranging from inhibiting soil microbial activity to

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contaminating groundwater and posing long-term human health risks (USEPA, 2012).

Despite these risks, there is a paucity of scientific data on the environmental distribution of explosive residues in Nigeria's North-East. No systematic study has yet quantified the levels of TNT, RDX, and HMX in Gwoza's soils and waters, nor assessed their potential risks to human and ecological health. Without this information, it is impossible to develop evidence-based remediation strategies or policy responses.

Materials and Methods

Study area and sampling design. Five sampling points (SP1–SP5) were established in Gwoza LGA, Borno State, Nigeria, representing all the Boko Haram post detonation locations at varying distances and hydrologic positions relative to detonation sites and likely flow paths. At each point, soil and surface-water samples were collected in triplicate to estimate mean concentrations and their standard deviations (SD). Units are mg/kg (soil) and mg/L (water) (USEPA 2002). Soil samples were collected from 0–15 cm depth within 50 m, 100 m, and 200 m radii of identified explosion craters. Control samples of both Soil and water were taken from Shani local government area where there is no Boko Haram/Military activities at the sites, a total of 30 soil and water samples were collected.

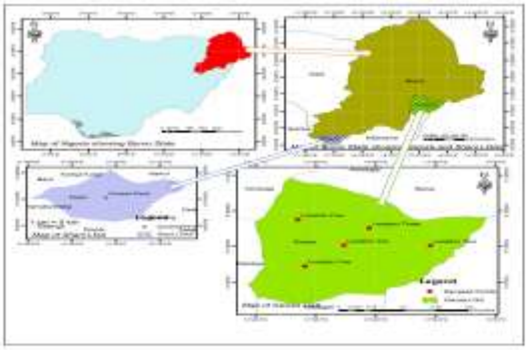

Figure: 1. Map of the study area and control site showing sampling points

Sample Preparation, Extraction, and Analysis

Soil samples were air-dried at ambient temperature, homogenized, and sieved to <2 mm to remove coarse debris and ensure representative subsampling. Each homogenized sample (~10 g) was stored in amber glass containers at 4 °C prior to extraction. Water samples were filtered through 0.45 µm membrane filters to remove suspended particulates, following the protocol of Jenkins *et al.*, (2006). Both matrices were analyzed for nitroaromatic and nitramine explosives including TNT, RDX, HMX, 2,4-DNT, 2,6-DNT, DNB, TNB, nitrophenol (NP), and nitrotoluene (NT).

Extraction and Cleanup

For soils, extraction was carried out using acetonitrile as the solvent in a mechanical shaker for 18 hours at room temperature, following a modified USEPA SW-846 Method 8330B protocol (USEPA 2020). Extracts were filtered and concentrated using rotary evaporation under nitrogen stream. Water samples were subjected to solid-phase extraction (SPE) using C18 cartridges (500 mg / mL), eluted with acetonitrile, and reduced to 1 mL final volume.

Instrumental Analysis

Quantification was carried out using Gas Chromatography-Mass Spectrometry (GC-MS) with an Agilent 7890 gas chromatograph connected to a 5977B mass selective detector. We operated it in selected-ion monitoring (SIM) mode. For the analysis, a HP-5MS capillary column was used, measuring 30 meters in length, with a 0.25 mm inner diameter and 0.25 µm film thickness. Helium was used as the carrier gas at a flow rate of 1.0 mL/min. The injector temperature was set to 250 °C and was run in splitless mode. The oven temperature program started at 80 °C, where it was held for one minute, then increased to 280 °C at a rate of 10 °C per minute, and remained at that temperature for an additional five minutes. To ensure accurate results, calibration curves were prepared using certified analytical standards from Sigma-Aldrich, ranging from 0.01 to 10 mg/L for water samples and from 0.1 to 10 mg/kg for soil samples. The calibration showed excellent reliability, with coefficients of determination (R^2) greater than 0.995.

Quality Assurance and Detection Limits

We made sure to include procedural blanks, matrix spikes, and triplicate samples in all our analyses to ensure both precision and accuracy. We also verified the instrument calibration every ten samples by using mid-range standards. The method detection limits (MDLs) we found ranged from 0.05 to 0.10 mg/L for water and 0.20 to 0.50 mg/kg for soil, which aligns with

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values reported in the literature (USEPA 2020; Mystrioti et al., 2024). Additionally, we had average recoveries for TNT, 2,4-DNT, and 2,6-DNT between 88% and 106%, demonstrating satisfactory performance in our analytical methods.

Statistical analysis

For each compound and matrix (soil, water), one-way ANOVA was conducted across the five sampling points using summary statistics (group means, SDs, n=3). Between-group sum of squares (SS_between) was computed as Σ n_i(μ_i − μ̄)^2 and within-group sum of squares (SS_within) as Σ (n_i − 1)·s_i^2, where μ_i and s_i are the group mean and SD. F-ratios were obtained as MS_between/MS_within, p-values from the F distribution, and effect sizes as η^2 = SS_between / (SS_between + SS_within). Non-detects (means and SDs reported as zero) were retained but yield undefined F where within-group variance is zero.

Results

Descriptive statistics (mean ± SD) for soils and waters are summarized in Tables 1–2.

Table 1. Mean concentrations (mean ± SD, mg/kg) of explosives remnants in Soil from various Boko Haram detonation sites

Sampling Point	TNT	RDX	2,6-DNT	TNB	HMX	DNB	2,4-DNT	NP	NT
SP1	0.00767 ± 0.00058	0.00000 ± 0.00000	1.00367 ± 0.00153	0.05167 ± 0.00153	0.00000 ± 0.00000	0.04167 ± 0.00153	6.14067 ± 0.00115	0.12067 ± 0.00115	0.01433 ± 0.00153
SP2	0.18200 ± 0.00200	0.00000 ± 0.00000	0.00767 ± 0.00153	0.00867 ± 0.00058	0.00000 ± 0.00000	0.00167 ± 0.00115	6.04067 ± 0.00115	0.01333 ± 0.00153	0.00767 ± 0.00153
SP3	0.18200 ± 0.00200	0.00000 ± 0.00000	0.00767 ± 0.00153	0.00867 ± 0.00058	0.00000 ± 0.00000	0.00167 ± 0.00115	6.04067 ± 0.00115	0.01333 ± 0.00153	0.00767 ± 0.00153
SP4	0.16133 ± 0.00153	0.00000 ± 0.00000	1.25067 ± 0.00305	0.00667 ± 0.00115	0.00000 ± 0.00000	0.06367 ± 0.00115	7.01967 ± 0.00153	0.15067 ± 0.00208	0.09367 ± 0.00058
SP5	0.00733 ± 0.00153	0.00000 ± 0.00000	0.09167 ± 0.00153	0.00433 ± 0.00153	0.00000 ± 0.00000	0.00167 ± 0.00115	5.13133 ± 0.00231	0.01100 ± 0.00100	0.00767 ± 0.00153

Table 2. Mean concentrations (mean ± SD, mg/L) of explosives remnants in Water near from various Boko Haram detonation sites.

Sampling Point	TNT	RDX	2,6-DNT	TNB	HMX	DNB	2,4-DNT	NP	NT
SP1	0.00233 ± 0.00058	0.00000 ± 0.00000	0.00233 ± 0.00058	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00367 ± 0.00058	0.00167 ± 0.00058	0.00633 ± 0.00058
SP2	0.00133 ± 0.00058	0.00000 ± 0.00000	0.00133 ± 0.00058	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00500 ± 0.00100	0.00167 ± 0.00058	0.00167 ± 0.00058
SP3	0.00567 ± 0.00058	0.00000 ± 0.00000	0.00367 ± 0.00058	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00133 ± 0.00058	0.00267 ± 0.00058	0.00367 ± 0.00058
SP4	0.00400 ± 0.00100	0.00000 ± 0.00000	0.00367 ± 0.00058	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00000 ± 0.00000	0.00200 ± 0.00100	0.00267 ± 0.00058	0.00133 ± 0.00058

SP5	**0.00133 ± 0.00058**	**0.00000 ± 0.00000**	**0.00133 ± 0.00058**	**0.00000 ± 0.00000**	**0.00000 ± 0.00000**	**0.00000 ± 0.00000**	**0.00133 ± 0.00058**	**0.00133 ± 0.00058**	**0.00167 ± 0.00058**

Table 3. One-way ANOVA across sampling points for soils (per compound).

Compound	**df_between**	**df_within**	**MS_between**	**MS_within**	**F**	**p_value**	**eta_squared**
2,4-DNT	**4**	**10**	**1.342187**	**0.000002**	**576318.219**	**1.11e-16**	**1.000**
2,6-DNT	**4**	**10**	**1.098641**	**0.000004**	**294287.880**	**1.11e-16**	**1.000**
DNB	**4**	**10**	**0.002522**	**0.000002**	**1652.754**	**4.707e-14**	**0.998**
HMX							
NP	**4**	**10**	**0.013982**	**0.000002**	**6170.032**	**1.11e-16**	**1.000**
NT	**4**	**10**	**0.004292**	**0.000002**	**2212.570**	**1.099e-14**	**0.999**
RDX							
TNB	**4**	**10**	**0.001202**	**0.000001**	**900.304**	**9.748e-13**	**0.997**
TNT	**4**	**10**	**0.025497**	**0.000003**	**9793.009**	**1.11e-16**	**1.000**

Table 4. One-way ANOVA across sampling points for waters (per compound).

Compound	**df_between**	**df_within**	**MS_between**	**MS_within**	**F**	**p_value**	**eta_squared**
2,4-DNT	**4**	**10**	**0.000008**	**0.000001**	**13.046**	**0.0005588**	**0.839**
2,6-DNT	**4**	**10**	**0.000004**	**0.000000**	**12.259**	**0.0007185**	**0.831**
DNB							
HMX							
NP	**4**	**10**	**0.000001**	**0.000000**	**3.488**	**0.04963**	**0.582**
NT	**4**	**10**	**0.000013**	**0.000000**	**39.780**	**4.123e-06**	**0.941**
RDX							
TNB							
TNT	**4**	**10**	**0.000011**	**0.000000**	**22.594**	**5.399e-05**	**0.900**

Spatial patterns. Soil concentrations substantially exceeded water concentrations for most compounds, indicating strong retention in the soil matrix (*Sikar et al.*, 2025). Soil 2,4-DNT was consistently elevated at all points and highest at SP4 (7.01967 ± 0.00153 mg/kg), while soil 2,6-DNT showed marked spatial contrast with hotspots at SP4 (1.25067 ± 0.00305 mg/kg) and SP1 (1.00367 ± 0.00153 mg/kg) but near-background levels at SP2–SP3. Soil TNT peaked at SP2–SP3 (~0.182 ± 0.002 mg/kg) and was lowest at SP1 and SP5 (~0.007–0.008 mg/kg). Across water samples, all analytes were one to three orders of magnitude lower, with detectable yet small peaks for TNT (SP3–SP4) and 2,4-DNT (SP2).

ANOVA outcomes. Using triplicate-based summary ANOVA, several soil compounds

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exhibited strong evidence of spatial heterogeneity among sampling points, reflected in large F-statistics and small p-values, and large effect sizes (η^2). In contrast, many water-phase analytes showed limited variance and/or values near detection, yielding weak or undefined F-tests. The effect sizes for key soil analytes (TNT, 2,4-DNT, 2,6-DNT) were typically ≥ 0.8, implying that the majority of variance is attributable to differences among locations rather than within-point variability.

Figures 2–7 illustrate key spatial contrasts using bar charts with error bars (mean ± SD).

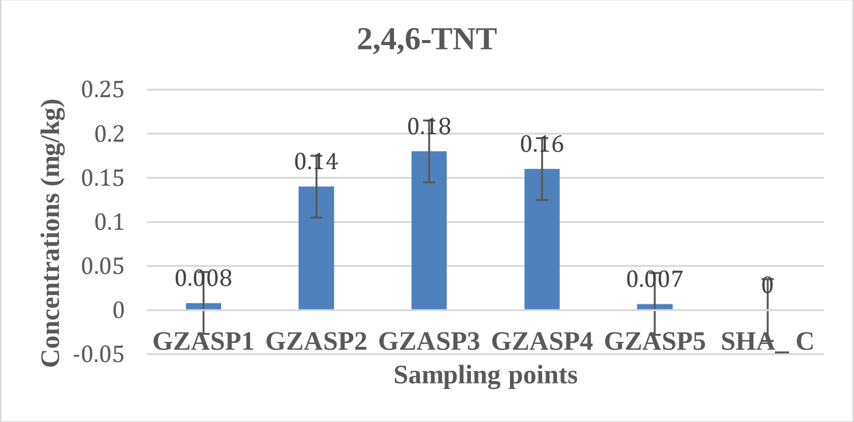

Figure: 2. Distribution of TNT in different Soil sampling point

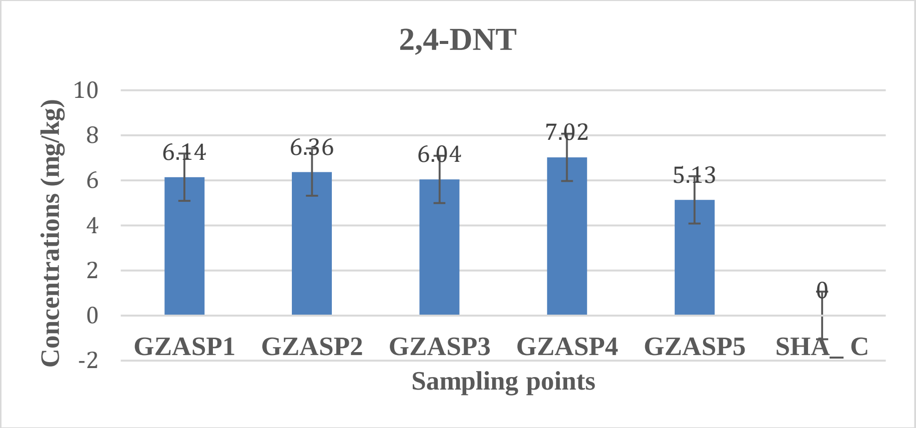

Figure: 3. Distribution of 2,4-DNT in different Soil sampling point

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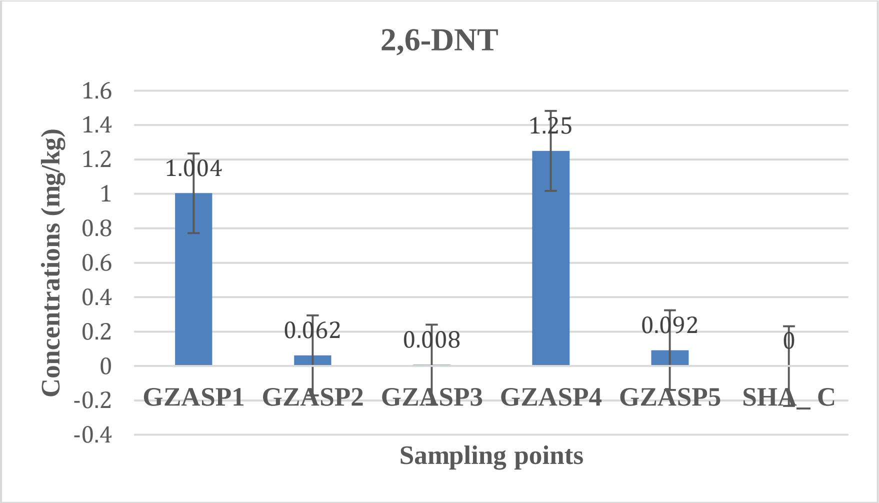

Figure: 4. Distribution of 2,6-DNT in different Soil sampling point

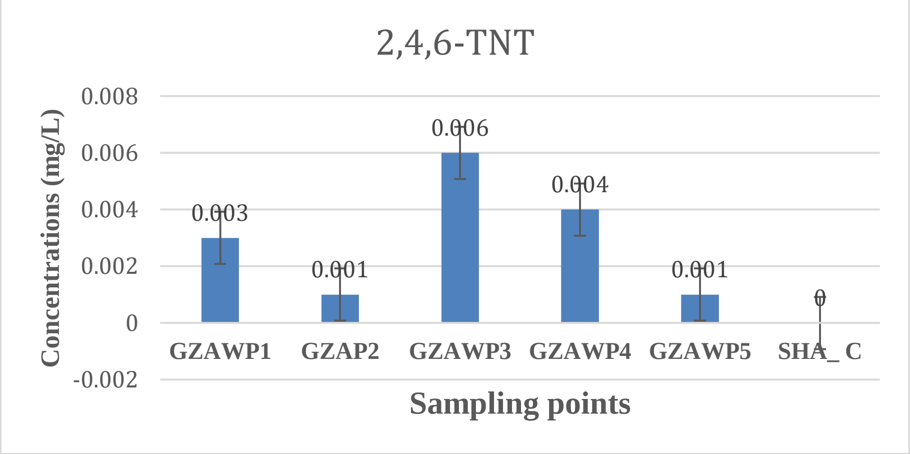

Figure: 5. Distribution of TNT in different Water sampling point near detonation sites

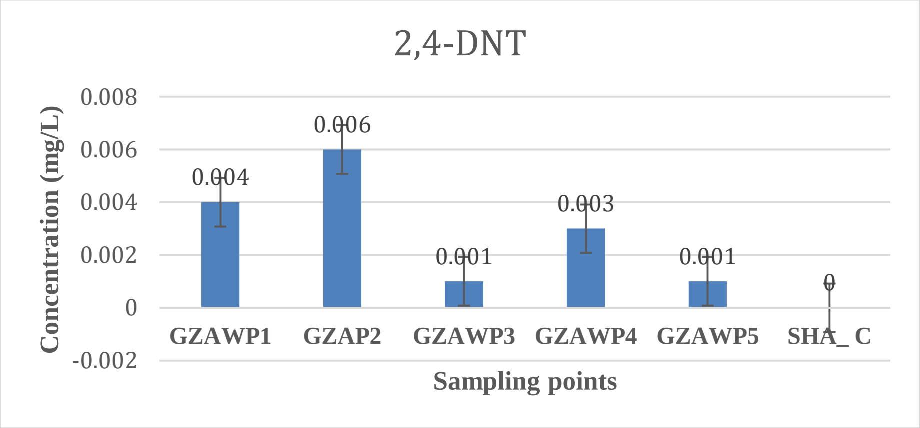

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Figure: 6. Distribution of 2,4-DNT in different Water sampling point near detonation sites

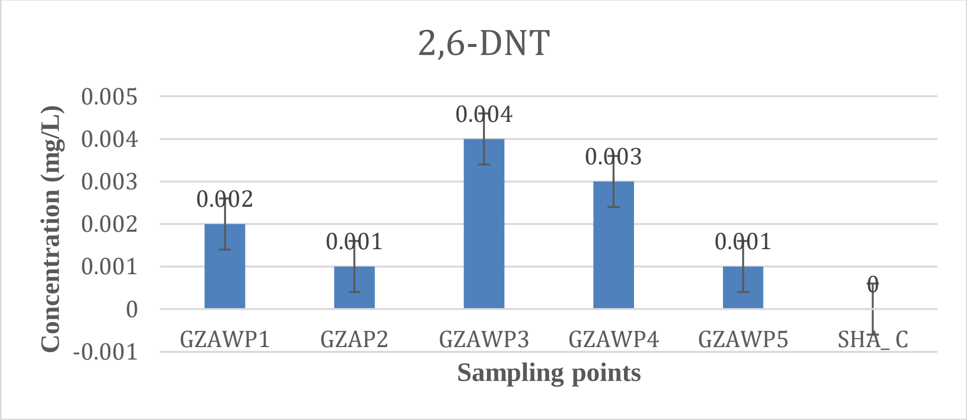

Figure: 7. Distribution of 2,6-DNT in different Water sampling point near detonation sites

Discussion

As shown in Figure 1 to 4, high concentrations of nitroaromatics in soils, especially 2,4-DNT and 2,6-DNT at SP4 and TNT at SP2–SP3 are consistent with (i) proximity to detonation/ordnance handling zones, (ii) high organic matter or fine-textured soils promoting sorption, which reduces leaching and increases residence time, and (iii) redox-mediated transformation of TNT to DNT isomers within reducing microsites (Yu *et al*., 2017). The small SDs relative to means indicate both analytical precision and limited micro-scale heterogeneity at the sampling resolution, lending confidence to the observed spatial gradients (Xu *et al*., 2025). Whereas the concentrations explosives in water sample from all the sampling points as shown in Fig. 5 to 7 remain low due to rapid dilution, photolysis in sunlit surface waters, sediment sorption, and episodic hydrologic connectivity that exports pulses rather than sustaining dissolved plumes (Pennington *et al*., 2002). Lower soil TNT at SP1 and SP5 may reflect longer weathering histories, greater exposure to oxygen (favoring aerobic biodegradation), and/or coarser textures with reduced sorption capacity.

Soil–water partitioning: The strong soil signature relative to water is consistent with published partitioning behavior of nitroaromatics and nitramines. Sorption to organic carbon and Fe/Al oxides, combined with restricted infiltration under semi-arid conditions, limits dissolved transport (Zhang *et al*., 2009). Where water peaks occur (e.g., TNT at SP3–SP4; 2,4-DNT at SP2), they likely correspond to runoff events, bank erosion, or seepage concentrating recently mobilized residues.

Implications for Risk and Management: The statistical analysis has identified certain hotspots that require special attention, specifically at sampling point SP4 for 2,4-DNT and 2,6-DNT, and at SP2–SP3 for TNT. It is essential to conduct targeted risk assessments in these areas, which may include pathway-specific health and risk evaluations and potential remediation efforts. To reduce risk, management strategies should focus on minimizing erosion, stabilizing riverbanks, and intercepting storm water near these hotspots to prevent contamination from spreading off-site. Additionally, long-term monitoring should incorporate sediment and porewater analysis, alongside other important measurements like pH, redox potential, dissolved organic carbon (DOC), grain size, and microbial assessments to better understand the potential for natural transformation of these contaminants.

Summary

This study explores the distribution, environmental behavior, and associated risks of explosive residues, particularly TNT, RDX, HMX, and DNT isomers, in soils and surface waters at detonation sites in Gwoza LGA, North-East Nigeria. Sampling across five points (SP1–SP5) has revealed significantly higher concentrations of nitroaromatic compounds in the soils compared to the water, suggesting that the soil retains these contaminants while they do not easily move into the water. ANOVA analysis has shown clear spatial differences in

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contamination levels, particularly highlighting hotspots for TNT and DNT isomers at SP2–SP3 and SP4. Low levels found in water can likely be attributed to processes like photolytic degradation, dilution, and sorptive retention, while the higher soil concentrations indicate ongoing contamination due to past detonation activities and limited natural cleanup. When compared to global data from 2022–2025, these findings reveal similar contamination patterns in areas experiencing conflict. Overall, this study supports the urgent need for targeted remediation efforts, erosion control, and the expansion of monitoring processes that examine sediment, porewater, and living organisms in the area. Recommended actions include detailed soil profiling, assessing the feasibility of microbial and bioremediation strategies, and evaluating health risks specific to various pathways. This work establishes an essential baseline for post-conflict environmental management in this region of Nigeria.

Conclusion

This investigation highlights significant spatial variability in explosive residue concentrations within the soils of Gwoza, with lower levels found in water. The summary statistics from ANOVA indicate noteworthy differences between sites for key soil contaminants, underscoring that there are distinct sources and specific local factors impacting retention and transformation. These results provide a solid foundation for risk assessments and help prioritize the necessary mitigation efforts at key locations, particularly at SP4 and other sites with elevated contamination levels.

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