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Characterization and Development of Quality Indices for Sites Contaminated with High Energy Materials

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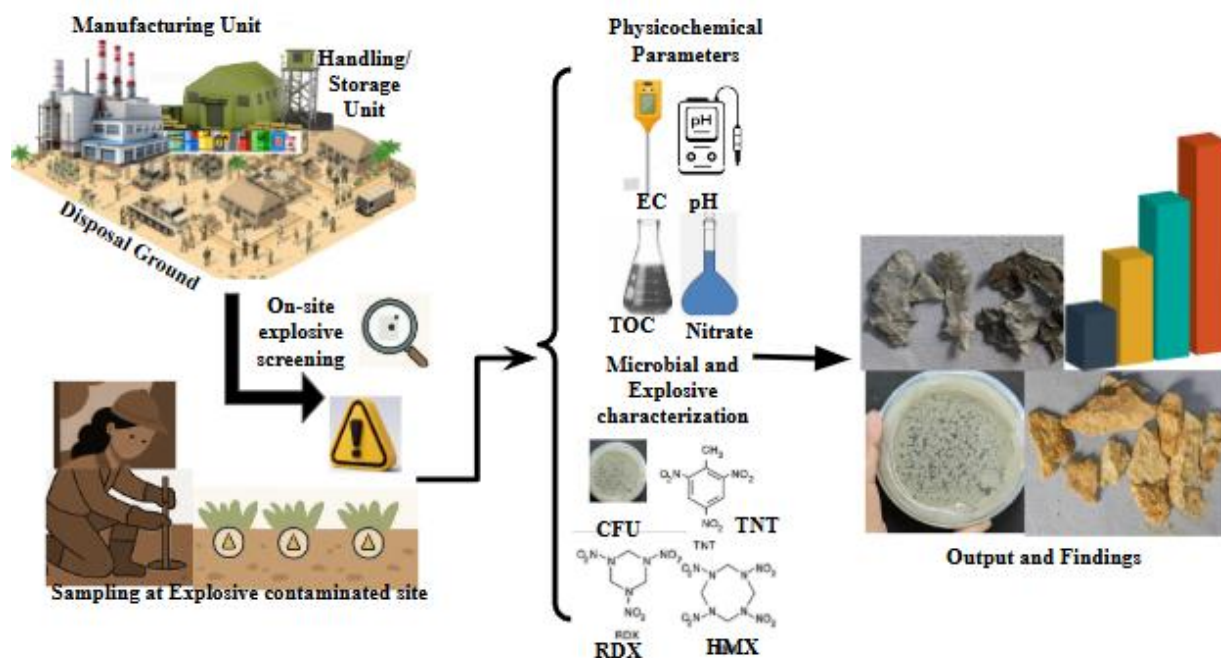
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Graphical Abstract:



Abstract

Improper handling and disposal of high energy materials during manufacturing, testing and training operations can cause severe pollution of soil and groundwater ecosystems. Characterizing potentially explosive contaminated sites is critical for assessing environmental risks and determining appropriate remediation strategies. The present study was carried out to evaluate the soil quality of three sites at explosive handling units in India. Samples were collected from the sites using the systematic random sampling method. These samples were subjected to air drying for 24 hours and were characterized for different physicochemical parameters. Soil analysis confirmed widespread soil contamination by high energy materials across all the three sites. Site-I exhibited RDX, HMX, and TNT concentrations of 7046.7, 1620.34, and 289.10 mg/Kg respectively. Site -II exhibited predominant contamination by RDX and HMX at 29,967 and 16,626 mg/Kg and while site- III contained RDX and TNT at 428.85 and 2328.96 mg/Kg indicating significant contamination beyond regulatory limits for industrial soils in these three sites. Soil Quality Index (SoQI) was found to be in the range of 30-35, which classifies these sites to be of high level of concern. EQI results classify the site to be moderate to poorly degraded. These results serve as a valuable database for developing remediation technology to decontaminate such sites. The findings also contribute to the broader understanding of site-specific factors influencing contaminant behavior and remediation efficacy, ultimately supporting the implementations of a sustainable remediation technology for restoration of these sites.

Keywords: Site characterization, Soil Quality, Environmental Safety, Decontamination, Bioremediation, Explosives

List of Abbreviations

39	RDX	Royal Demolition Explosive 1,3,5-Trinitro-1,3,5-triazinane
40	HMX	High Melting Explosive 1,3,5,7-Tetranitro-1,3,5,7-tetrazocane
41	TNT	Trinitro Toulene
42	DNT	Dinitro Toulene
43	SoQI	Soil Quality Index
44	EQI	Environmental Quality Index
45	HEM	High Energy Material
46	USEPA	United State Environmental Protection Agency
47	CFU	Colony Forming Unit
48	OECD	Organisation for Economic Co-operation and Development
49	UHPLC	Ultra High Pressure Liquid Chromatography
50	OD	Optical Density
51	TOC	Total Organic Carbon
52	TN _b	Total bound Nitrogen
53	SFI	Soil Function Index
54	CLI	Contaminant Load Index
55	CF	Contamination Factor
56	WHC	Water Holding Capacity
57	CEC	Cation Exchange Capacity
58	SAR	Sodium Absorption Ratio
59		
60	1. Introduction	

High energy materials (HEMs) handling facilities represent a distinct class of industrial site characterized by the recurrent release of energetic compounds into surrounding environmental matrices (Agrawal, 2010). Activities such as production, machining and cutting of explosive components, open burning and open detonation, storage, transport and demilitarization activities generate residues of nitroaromatic, nitramine, and nitrate ester compounds along with combustion by-products and nitrogen-rich intermediates (Krauter et al. 1999; Singh and Steevens, 2005). Unlike conventional industrial pollutants, energetic materials exhibit complex environmental behavior governed by their physicochemical reactivity, persistence, sorption–desorption dynamics, and transformation pathways (Jenkins et al. 2006). Consequently, soils and sediments at HEM depots function not only as sinks but also as potential secondary sources of contamination, posing risks to terrestrial ecosystems and groundwater resources (EPA, 2004).

Environmental assessment of explosive-contaminated sites has traditionally focused on quantification of residual energetic compounds (Lewis et al. 2001). While contaminant concentration remains a critical metric, reliance on single-parameter chemical assessment provides only a partial understanding of environmental impact (Spain et al. 2000). Soil and sediment systems are dynamic ecological matrices whose functionality depends on tightly coupled physical, chemical, and biological processes (Reddy et al. 2006). Alterations in pH, electrical conductivity, organic matter content, nutrient availability, and redox conditions directly influence the mobility, bioavailability, and degradation of energetic compounds (Sunahara et al. 2012). Simultaneously, contamination may disrupt microbial communities, nutrient cycling processes, and trophic interactions (Brady and Weil, 2016). Therefore, comprehensive characterization of HEM-impacted sites must extend beyond contaminant load and incorporate indicators of ecological integrity and functional stability (Hatzinger and Alexander, 1995).

Soil physicochemical properties such as texture, moisture regime, bulk density, and porosity regulate contaminant transport and retention (Rylott and Bruce 2019). Organic carbon and organic matter content play a central role in governing adsorption behavior, sequestration potential, and microbial-mediated transformation of energetic compounds (Adams et al. 2015). Nitrogen fractions, including total bound nitrogen and inorganic nitrogen species, reflect alterations in nutrient cycling that may arise from both contamination and site-specific operational inputs (Mukherjee and Lal, 2014). Variations in these parameters can significantly modify soil buffering capacity and ecological resilience (Pennington et al. 2002a). In parallel, biological indicators such as colony forming units (CFU) and microbial abundance provide insight into the adaptive response or stress experienced by indigenous microbial populations (Bünemann et al. 2018). Because microorganisms are primary agents of biodegradation, shifts in microbial density and activity serve as early indicators of ecosystem perturbation (Spain, 1995).

Despite the availability of diverse environmental parameters, interpretation of high-dimensional datasets from contaminated depots remains a significant challenge. Individual measurements, although informative, often yield fragmented insights when considered independently. Therefore there is a need for integrative tools that synthesize multi-domain data into coherent and interpretable metrics (Andrews et al. 2004). Environmental indices provide a scientifically robust means to translate complex datasets into composite scores that reflect overall system condition (Karlen and Stott, 1994). A Soil Quality Index (SoQI) integrates selected physical, chemical, and biological parameters to evaluate the functional capacity of soil as a living system (Mukherjee and Lal, 2014). By normalizing variables, reducing redundancy, and assigning ecological weights based on relative importance, SoQI transforms multidimensional observations into a single quantitative descriptor of soil health (Karlen and Stott, 1994). Such an index enables comparative

evaluation across sites, operational units, and depth profiles, thereby facilitating systematic monitoring.

However, soil quality assessment alone may not fully capture broader environmental risks associated with energetic material depots. Environmental contamination extends beyond in situ soil functionality and includes considerations of contaminant toxicity, ecological receptor response, and potential off-site migration (Swamee and Tyagi, 2000). To address this broader scope, the development of an Environmental Quality Index (EQI) becomes essential (Singh et al. 2017). The EQI integrates contaminant concentration, soil functional indicators, biological response parameters, and mobility characteristics into a comprehensive framework of environmental risk (OECD, 2001). Incorporation of leachability assessment is particularly important, as total contaminant concentration does not necessarily correspond to environmental hazard. Mobility under simulated precipitation conditions provides insight into groundwater contamination potential and long-term liability. By integrating leachability with toxicity endpoints and physicochemical parameters, EQI shifts environmental assessment from static characterization toward predictive risk evaluation (USEPA 2014).

Ecotoxicological validation represents a critical bridge between index development and ecological relevance. Physicochemical indices must be corroborated by biological responses to ensure that composite scores meaningfully reflect organism-level effects. Earthworms serve as key bioindicators of soil ecosystem health due to their ecological role in nutrient cycling, soil aeration, and organic matter turnover (Lanno et al. 1999). Short-term exposure assays assessing survival, behavioral response, biomass variation, and mortality provide direct evidence of bioavailable toxicity within contaminated matrices (Gong et al. 1999). Similarly, phytotoxicity assays using representative plant species offer insight into early-stage growth inhibition, germination

impairment, and shoot development constraints (Sverdrup et al. 2001). Seed emergence, percentage germination, and biomass accumulation collectively reflect the suitability of soil or sediment to support primary productivity. The integration of macrofaunal and plant-based bioassays enables cross-trophic validation of index-derived environmental classifications (Rocheleau et al. 2008).

Sediments associated with explosive handling and manufacturing facilities warrant particular attention, as they frequently act as repositories of transported contaminants (Pennington et al. 2001). Runoff during precipitation events mobilizes surface residues into drainage channels and depositional zones, where sediments may accumulate higher contaminant loads than adjacent soils (Clausen et al. 2006). Sediment matrices differ from upland soils in terms of redox conditions, organic matter distribution, and microbial community structure, potentially altering contaminant fate and ecological impact. Inclusion of both soil and sediment matrices within a unified monitoring framework strengthens environmental interpretation and supports holistic site management.

In many industrial contexts, systematic multi-parameter environmental assessment of explosive depots remains limited (Suter, 1993). Existing studies often focus on isolated contaminant measurements without integrating functional soil health indicators or ecotoxicological validation. Furthermore, the application of composite environmental indices tailored to high-energetic material facilities is scarce (Chapman, 2007). The absence of standardized frameworks hampers consistent monitoring, inter-site comparison, and evidence-based decision-making. An integrated approach that combines comprehensive physicochemical characterization, biological assessment, contaminant quantification, leachability evaluation, and index-based synthesis can provide a scientifically defensible model for environmental surveillance of such facilities (USEPA, 1998).

The present study addresses this gap by conducting extensive multi-parameter characterization of soils from two high-energetic material depots and sediments from a third operational location. Physical, chemical, and biological parameters were analyzed alongside quantification of explosive residues. Soil quality and Environmental quality Indices were developed to integrate these parameters into composite measures of functional integrity and environmental risk. Ecotoxicological validation was performed using controlled earthworm exposure assays and phytotoxicity experiments with wheat and green gram, with uncontaminated soil serving as a reference control. Additionally, leachability testing was conducted to evaluate contaminant mobility under simulated precipitation conditions. By integrating multi-domain environmental indicators with biological validation and mobility assessment, this study proposes a comprehensive framework for environmental monitoring of explosive manufacturing and handling facilities, enabling site comparison, risk categorization, and informed decision-making.

2. Materials and methods

2.1 Site selection and description

Based on the accessibility and availability of sample collection ease three different sites were identified for site characterization. These sites are located in India and were designated as Site I, Site II and Site III. Site I is majorly a ballistics research site where manufacturing of explosives and cutting of ammunition parts takes place. Site II is a manufacturing and transportation facility and Site III is a waste disposal and ammunition depot facility where disposal of explosive contaminated waste is carried out by open burning and detonation. The industrial setup of these sites has more than 50 years of operational history. Site I has a subtropical monsoon climate, Site

II has tropical wet and dry climate while Site III has humid subtropical climate. The average annual temperature of all three sites is 23.6 °C and a mean annual precipitation of approximately 977.6 mm. The study area contains a workshop cutting area, testing range, storage facility, waste disposal ground and warehouse office area.

2.2 Onsite screening and sampling design:

Onsite explosive screening solutions were prepared to identify the potentially explosive contaminated site. Screening solutions were prepared for individual explosive viz. HMX, RDX and TNT as per the method suggested by Fiegl (1966). 2g soil samples from sites were taken in test tubes and reagents were added. The test tubes were shaken vigorously, and the color change was observed. Red color change indicates presence of HMX and blood red color indicates presence of RDX. TNT presence is indicated by appearance of reddish purple color and presence of DNT is screened by appearance of blue color. After onsite screening, flagging was done on the identified area, and quadrants were made. The site was proportionately gridded and distinctively marked based on different activities. The sampling method adopted for soil samples was the random sampling method as per USEPA, 2002. Increment sampling was done in each quadrant. Soil samples were collected from the surface and sub-surface (6 inches) in replicates from site I and III; from site II, sediment samples were collected.

2.3 Sample collection, sample handling, and preservation:

The soil samples were collected with the help of a spade and auger, in polypropylene plastic zip bags and were stored in an icebox for transportation. Sediment samples were collected separately in small drums and brought to the lab. Samples were stored at 4° C for analysis of various

physicochemical, heavy metal, and explosive concentration analysis. Composite samples for each site were obtained using the quartering technique. Safety protocols were adopted during sample collection and precautions were taken to avoid cross-contamination while transporting. After air drying (in shade) for 24 hours, soil samples were crushed gently in a ceramic pestle and mortar and sieved through a 2 mm stainless steel sieve. The grounded samples were stored in polythene bags. The grounded samples were mixed well before they were weighed for analysis. The samples were weighed on a sartorius analytical balance. Triplicate samples were taken for each set.

2.4 Characterization techniques:

Soil and sediment samples collected from three different locations were characterized for various physicochemical and biological parameters. Parameters calcium (as Ca), sodium (as Na), potassium (as K), magnesium (as Mg), available nitrogen (as N), available phosphorus and potassium, sodium absorption ratio, cation exchange capacity, boron, and hexavalent chromium (as Cr^{6+}) were analysed at Vardhan Envirolab LLP, Gurugram, India. The reference method adopted for other parameters is given in Table 1.

Table 1: List of parameters with the method adopted for analysis

S.N.	Parameters	Reference method
1.	pH	SW 846, 9045D: 2015
2.	EC	Rhoades et al. 1989
3.	Texture	Thien et al.1979
4.	Bulk Density	Ma et al. 2013
5.	Moisture Content	ICARDA,2013

6.	Organic Matter	ASTM D2974: 2025
7.	Water Holding Capacity	Soil testing protocol, Bhattadev University
8.	Organic Carbon	ISO 20236:2018 (E)
9.	Explosive (RDX, HMX, TNT)	USEPA 8330 B: 2006
10.	Nitrate	Norman 1965, Mercimek et al. 2013
11.	Nitrite	Norman 1965, Mercimek et al. 2013
12.	Sulphate	Nair et al. 2020
13.	CFU	ISO 20391-1: 2018
14	Color	USDA, NRCA: 2024
15.	Total Zinc (as Zn)	USEPA 6010D: 2018
16.	Total Manganese (as Mn)	USEPA 6010D: 2018
17.	Total Chromium (as Cr)	USEPA 6010D: 2018
18.	Total Lead (as Pb)	USEPA 6010D: 2018
19.	Iron	USEPA 6010D: 2018
20.	Total Mercury (as Hg)	USEPA 6010D: 2018
21.	Total Nickel	USEPA 6010D: 2018
22.	Total Copper	USEPA 6010D: 2018
23.	Total bound nitrogen	ISO 20236:2018 (E)

216

217 Metal analysis was performed using ICP-OES according to USEPA method 6010D after heat-
218 assisted acid digestion following USEPA method 3015A.

219

220 **2.4.1 Chemical analysis:**

Liquid chromatography analysis was carried out using UHPLC (Thermo Scientific Inc.) All samples were analyzed as per standard methods by preparing 1:2 extract of soil in milli-Q water and ultrasonicated for 18 h at room temperature. C18 was used as a stationary phase with acetonitrile, 0.1% formic acid, and water as mobile phase. Flow rate was maintained at 0.3 mL/min with a run time of 6 mins, 5µL injection volume was used to detect the respective peaks of RDX, HMX and TNT.

Concentrations of nitrate, nitrite, and sulphate ions were measured spectrophotometrically (Mercimek et al. 2013; Kalsi et al. 2022). Sulphate ion determination was done by adding 5g of air-dried and sieved sample to 50 ml of distilled water to make a uniform suspension. Then 50 ml of filtrate was added to 10ml NaCl-HCl solution, and 10ml of Glycerol-ethanol solution and 0.15g of barium chloride, stirred with the help of a magnetic stirrer for about an hour. After filtration the supernatant was measured at 420 nm with sodium sulphate as standard using a spectrophotometer. TOC and TNb Analysis of samples were carried out using TOC analyser (M/s Elementar Enviro TOC).

The metal analysis was done by digesting the soil with 50 percent hydrogen peroxide and conc sulphuric acid in Hach's digestion apparatus at 440 degree celsius (USEPA 3015A, 2007). The samples were analysed using ICP-OES (M/s Analytik Jena, GmBH, Germany).

2.4.2 Physical and biological characterization:

Soil texture was determined by feel method (USDA and Thien, 1979). Soil moisture was determined gravimetrically after drying in a standard oven at a temperature of 105°C; bulk density was measured using tapped density method and weighing it on a compassionate sartorius analytical balance; conductivity and pH were determined using a pre-calibrated Metrohm microprocessor-

controlled pH/EC analyser. Water holding capacity of samples were calculated gravimetrically using Gooch crucible after keeping in the water bath for 20 mins. For total organic matter the oven dry samples were kept in a muffle furnace at 550°C for 5hr and the difference in weight of sample was recorded. Cell count was monitored using the plate count method.

2.5 Data analysis and development of quality indices:

Soil Quality Index (SoQI) and Environmental Quality Indices (EQI) were developed using the data set. The data set are represented through graphs made with MATLAB (version 2018). The tested parameters were compared with their permissible limits and evaluated for their scope, frequency and amplitude as per Canadian SoQI method (CEPA, 2007). F1 represents the percentage of contaminants that do not meet their respective guidelines (failed contaminants) relative to the total number of contaminants at the site. F2 represents the percentage of individual tests that do not meet their respective guidelines. F3 represents the amount by which failed test values do not meet their respective guidelines (excursion from the guideline value).

$$F1 = (\text{Number of failed contaminants} / \text{total number of contaminants}) * 100$$

$$F2 = (\text{Number of failed tests} / \text{total number of tests}) * 100$$

If the concentration of a contaminant is greater than (or less than, when the guideline is a minimum) the soil quality guideline, it is called an excursion. The magnitude of excursion of each test is calculated as follows:

When the test value must not exceed the guideline;

$$\text{Excursion}_i = (\text{Failed test value}_i / \text{guideline}_i) - 1$$

For the cases in which the test value must not fall below the guideline;

$$\text{Excursion}_i = (\text{guideline}_i / \text{Failed test value}_i) - 1$$

Then, the average sum of excursions or ‘ase’ is calculated by summing the excursion of all individual tests from their guidelines and dividing by the total number of tests that do not meet their guidelines as follows:

$$ase = \sum_{i=1}^n \text{Excursion}_i / \text{number of failed tests}$$

F3 is then calculated by an asymptotic function that scales the average sum of excursions (ase) to yield a range between 0 and 100.

$$F3 = ase / (0.01 ase + 0.01)$$

From the value of F1, F2 and F3, SoQI was calculated using the below equation:

$$\text{SoQI} = 100 - (\sqrt{(F1^2 + F2^2 + F3^2)} / 1.732)$$

The divisor (1.732) normalizes the resultant values to a range between zero and one hundred. Level of concern for each site was identified by the end of the test.

Level of concern	Soil ranking categories of the SoQI
Very low	90-100
Low	70-90
Medium	50-70
High	30-50
Very high	0-30

For EQI, Total data set, Minimum data set, Soil Function Index (SFI) and Contaminant Load Index (CLI) was calculated (Kahsay et al. 2025). Total data set constituted all the parameters analysed

during site characterization. The minimum data set for Soil function index and contaminant load index were identified after performing correlation analysis.

Parameters were categorized into contaminant load indicators (explosive residues, nitrogenous degradation products, and heavy metals) and soil function indicators (physicochemical properties, nutrient status, and microbial activity), to distinguish between pollution burden and ecological recovery of soil. Soil function index constituted physiochemical and biological parameters while contaminant load index constituted chemical parameters. SFI was computed by normalizing fertility-related soil parameters against their optimal ranges, while CLI was derived using concentration-to-standard ratios for explosive residues and associated ions/metals. The identified parameters for SFI were normalized as per below given formula:

For each soil parameter i :

$\text{Score}_i = \{ 1, \text{ if value lies within optimal/ acceptable range;}$

$X_i / X_{\text{opt}}, \text{ if below optimum; or}$

$X_{\text{opt}} / X_i, \text{ if above optimum}$

This keeps SFI bounded between 0 and 1, where:

1 = optimal soil function

0 = very poor soil condition

$$\text{SFI} = \sum \text{Score}_i / n$$

n = total number of parameters considered for SFI

The identified parameters for CLI were normalized as per below given formula:

For each contaminant j :

$$\text{Contamination Factor (CF)}_j = C_j / C_{\text{standard}}$$

Where:

305 C_j = measured concentration

306

307 C_{standard} = permissible/ threshold value

308

309
$$CLI = \sum (CF)_j / m$$

310 m = total number of parameters considered for CLI

311 The EQI was calculated by assigning a higher weightage to contamination stress (0.6) relative to
312 soil functionality (0.4), reflecting site-specific risk conditions. EQI was calculated as per the
313 formula given below and final grading for each site was developed:

314
$$EQI = 0.4 * SFI + 0.6 * CLI$$

315

EQI range	Environmental quality grade
< 10	Moderate
20	Poor
30	Moderate
40	Degraded
>50	Severely degraded

316

317 The Contamination Load Index (CLI) was computed as the arithmetic mean of individual
318 contamination factors (CF), where m represents the number of contaminant parameters included
319 in the assessment. A separate contamination degree (Cd) was not calculated, as the averaging

approach provided a normalized representation of contamination stress suitable for integration into the Environmental Quality Index (EQI).

2.6 Plant and Earthworm bioassay

Representative samples from three different sites were tested for their suitability to support plant and earthworm growth using methods adopted from OECD 207 and 208. Test No. 208 (Seedling Emergence and Seedling Growth Test) was performed using sterilized *Triticum aestivum* and *Vigna radiata* seeds. The seeds were sown in pots with contaminated soil and blank soil. The germination percentage and survival rate were calculated at the end of the 14 days test. 5 seeds per pot were sowed and watered regularly to maintain the required moisture content. Test no. 207 (earthworm growth test) was carried out using *Eisenia fetida*. The earthworms were acclimatized for 24 hours in clean soil. Gut voiding of earthworm was performed by keeping them on moist paper for 3 hours before exposing them to contaminated and blank soil. 5 worms (pre-weighed) were placed in each 500mL beaker for 375g soil with continuous light and 20+/- 2°C temperature for 14 days. Mortality at day 7 and 14 were observed and behavioral signs were recorded.

2.7 Contaminant mobility through leachability testing

A column study was also carried out using synthetic precipitation leaching method to examine the transport of contaminants across columns. The test was carried out to assess the leachability of contaminants. For the column test, a 24 inch column was taken and the top 5 inch was filled with contaminated soil from the site and the rest was filled with background soil of the same site.

Optimized water flow was maintained using a drip line and controller during the test. After completion of test samples at every 5 inch and leachate were collected for explosives analysis.

3. Results and discussion

3.1 Site selection and onsite screening:

Unburnt explosive containing chunks and debris was identified on site. In the chunks we can see nails, shells and coverings used during the defense equipment manufacturing. The yellow colored debris (shown in figure 1) is the leftover material contaminated with TNT residues after the treatment process. During site visit on-site explosive screening was carried out to identify the potentially contaminated site for sample collection. The method adopted for preparation of screening reagents was adopted from Munchal et al. 2021. The results and pictorial representation of results observed in soil samples collected on site is given below in table 2 and figure 1.

Fig.1



(a)



(b)

Figure 1(a): Debris and chunks of HEM found on the Site III during onsite screening and sample collection.

(b): Color change observed during site screening

Soil samples after processing were reduced to 6 samples, two from each site. Except for explosive analysis all six soil/sediment samples were analysed for other parameters. For explosive analysis total 10 samples were analysed including the sub surface samples. For convenience, all the samples from three different sites were labeled as described in Table 2.

Table 2: Sample code and description with results of onsite screening of soil samples.

S.N	Sample	Description	Location	Observation	Expected
-----	--------	-------------	----------	-------------	----------

	Code		Type		Contaminant
1.	TZ2 S	Site I; Classified location surface soil	Cutting area	Blood red color	RDX, HMX
2.	TZ2 SS	Site I; Classified location subsurface soil	Cutting area	Blood Red and purple	RDX, HMX, TNT
3.	TZ6 S	Site I; Classified location surface soil	Explosion site	Nil	NA
4.	TZ6 SS	Site I; Classified location subsurface soil	Explosion site	Blood red color	RDX, HMX
5.	OSediR	Site II; Classified location labyrinth RDX	Manufacturing site outlet	-	-
6.	OSediH	Site II; Classified location labyrinth HMX	Manufacturing site outlet	-	-
7	FD S	Site III; Classified location surface soil	Waste disposal open burning ground	Purple color	TNT
8.	FD SS	Site III; Classified location subsurface soil	Waste disposal open burning ground	Reddish purple color	TNT RDX
9.	FG S	Site III; Classified location surface soil	Open detonation pit	Reddish purple color	RDX, TNT
10.	FG SS	Site III; Classified location subsurface soil	Open detonation pit	Blood red color	RDX

378

379 **3.2 Characterization of collected samples**

380

381 3.2.1 Physiochemical and biological analysis

382 The physicochemical, biological, and heavy metal characteristics of soil and sediment samples
383 collected from different locations of the contaminated site were analyzed to evaluate spatial
384 variability and overall site condition. Values are expressed as mean $\pm$ standard deviation (n=3).

385 The results are provided in table 3 below:

386 Table 3: Mean value with standard deviation of different physiochemical, biological, heavy metals
387 and explosive analysis done during the characterization of sites.

S.No.	Parameters	Site I			Site II			Site III		
		TZ2	TZ6	Mean $\pm$ SD	OHSedi	ORSedi	Mean $\pm$ SD	FD	FG	Mean $\pm$ SD
1.	pH	6.10	5.60	5.85 $\pm$ 0.35	6.20	5.90	6.05 $\pm$ 0.21	6.20	5.30	5.75 $\pm$ 0.64
2.	EC (mS/cm)	0.39	0.46	0.43 $\pm$ 0.05	0.27	0.41	0.34 $\pm$ 0.10	0.29	0.48	0.39 $\pm$ 0.13
3.	Moisture Content (%)	0.30	2.60	1.45 $\pm$ 1.63	0.80	0.70	0.75 $\pm$ 0.07	1.50	2.70	2.10 $\pm$ 0.85
4.	Organic Matter (%)	3.23	5.11	4.17 $\pm$ 1.33	2.29	3.88	3.09 $\pm$ 1.12	17.14	3.42	10.28 $\pm$ 9.70
5.	Water Holding Capacity (%)	26.14	13.91	20.03 $\pm$ 8.65	35.27	27.33	31.30 $\pm$ 5.61	16.21	11.86	14.04 $\pm$ 3.08
6.	Organic Carbon (%)	1.87	2.96	2.42 $\pm$ 0.77	1.26	2.25	1.76 $\pm$ 0.70	9.94	1.98	5.96 $\pm$ 5.63
7.	Total Bound Nitrogen (mg/kg)	7.30	70.50	38.90 $\pm$ 44.69	48.30	148.40	98.35 $\pm$ 70.78	58	104.10	81.05 $\pm$ 32.60
8.	TNT (mg/kg)	0	310.93	310.93 $\pm$ 30.8	0	0	0	30.26	4214.38	2122.32 $\pm$ 2958.62

9.	RDX (mg/kg)	61.37	14080.99	7071.18 $\pm$ 9913.37	0	19077.20	19077.20 $\pm$ 409.9	835.59	21.82	428.86 $\pm$ 575.63
10.	HMX (mg/kg)	87.44	2654.10	1370.77 $\pm$ 14.90	17180.09	0	17180.09 $\pm$ 609.7	0	0	0
11.	Nitrate (mg/kg)	12.50	19.41	12.50 $\pm$ 4.89	14.30	10.50	12.40 $\pm$ 2.69	13	10.50	11.75 $\pm$ 1.77
12.	Nitrite (mg/kg)	4.80	11.72	8.26 $\pm$ 4.89	8.06	9.66	8.86 $\pm$ 1.13	9.97	5	7.49 $\pm$ 3.51
13.	Sulphate (mg/kg)	42.50	62.34	52.42 $\pm$ 14.03	40.64	41.98	41.31 $\pm$ 0.95	79.38	16.16	47.77 $\pm$ 44.70
14.	CFU (x 10 ⁴ per gram soil)	3	5	4 $\pm$ 1.4	7	8	8 $\pm$ 0.7	4	2	3 $\pm$ 1.41
15.	Calcium (as Ca) (mg/Kg)	729.56	3305.70	2017.63 $\pm$ 1821.61	3888.05	191.67	2039.86 $\pm$ 2613.74	114.90	6754.36	3434.63 $\pm$ 4694.81
16.	Sodium (as Na) (mg/Kg)	25.78	68.44	47.11 $\pm$ 30.17	82.23	30.65	56.44 $\pm$ 36.47	36.21	310.54	173.38 $\pm$ 193.98
17.	Potassium (as K) (mg/Kg)	83.90	49.01	66.46 $\pm$ 24.67	84.98	19.46	52.22 $\pm$ 46.33	25.73	1752.40	889.07 $\pm$ 1220.94
18.	Magnesium (as Mg) (mg/Kg)	360.84	1083.67	722.26 $\pm$ 511.12	1196.06	81.35	638.71 $\pm$ 788.22	17.14	1663.63	840.39 $\pm$ 1164.24

19.	Available nitrogen (as N) (mg/Kg)	45.68	70.00	57.84 ± 17.19	60	82.45	71.23 ± 15.87	31.93	51.16	41.54 ± 13.60
20.	Available phosphorus (mg/Kg)	1.42	2.23	1.82 ± 0.57	10.78	1.28	6.03 ± 6.72	1.10	2.19	1.64 ± 0.77
21.	Total Zinc (as Zn) (mg/kg)	1.12	3.36	2.24 ± 1.58	0.60	0.41	0.51 ± 0.14	7.66	5.74	6.70 ± 1.36
22.	Total Manganese (as Mn) (mg/kg)	10.39	6.88	8.64 ± 2.48	17.97	1.71	9.84 ± 11.50	9.66	13.54	11.60 ± 2.74
23.	Total Chromium (as Cr) (mg/kg)	0.23	2.42	1.32 ± 1.55	0.30	0.70	0.50 ± 0.28	0.35	0.40	0.37 ± 0.03
24.	Total Lead (as Pb) (mg/kg)	0.14	12.22	6.18 ± 8.54	11.07	12.39	11.73 ± 0.93	0.40	97.46	48.93 ± 68.64
25.	Cation exchange capacity (meq./litre)	19.56	16.12	17.84 ± 2.44	10.82	14.16	12.49 ± 2.36	15.38	15.12	15.25 ± 0.19
26.	Boron (mg/kg)	4.47	6.44	5.46 ± 1.39	5.40	1.92	3.66 ± 2.46	6.27	34.98	20.63 ± 20.30
27.	Iron (mg/kg)	192.46	301.60	247.03 ± 77.17	198.62	293.80	246.21 ± 67.30	214.80	159.20	$187.00 \pm$

										39.32
28.	Sodium absorption ratio	0.8	1.0	0.91 ± 0.18	1.2	1.9	1.50 ± 0.49	2.7	3.4	3.0 ± 0.50
29.	Available potassium (mg/kg)	280	260	270.00 ± 14.14	300	245	272.50 ± 38.89	275	245	260.00 ± 21.21
30.	Hexavalent chromium (as Cr ⁶⁺) (mg/kg)	0.30	0.25	0.28 ± 0.04	0.28	0.32	0.30 ± 0.03	0.27	0.32	0.30 ± 0.04
31.	Total Mercury (as Hg) (mg/Kg)	0.01	0.07	0.04 ± 0.04	0.02	0.15	0.08 ± 0.09	0.05	0.12	0.09 ± 0.05
32.	Total Copper (mg/Kg)	0.39	0.72	0.55 ± 0.24	0.40	0.50	0.45 ± 0.07	10.18	0.58	5.38 ± 6.79
33.	Total Nickel (mg/Kg)	0.35	0.72	0.53 ± 0.26	0.52	0.03	0.27 ± 0.35	0.81	0.29	0.55 ± 0.37
34.	Bulk Density (gm/cc)	1.1	1.18	1.14 ± 0.06	1.25	1.05	1.15 ± 0.14	1.12	1.05	1.085 ± 0.05
35.	Texture	Sandy	Sandy	Sandy Loam	-	-	-	Loamy	Loamy	Loamy Sand

		Loam	Loam					Sand	Sand	
36.	Color	Dark brownish sh	Dark brownish	Dark brownish	Yellowish h	Yellowish	Yellowish	Light Brown	Light Brown	Light Brown

389

The notable standard deviation in explosive, macronutrients, and heavy metal concentrations suggests significant local variability within the contaminated site. This indicates that pollutants and soil physicochemical qualities are unevenly distributed across the studied area, most likely due to localized deposition, operational activities, and differential transport processes. Such heterogeneity is frequently reported in military training and munitions handling regions due to multiple contamination sources, localized deposition of explosive residues, variability in soil physicochemical qualities, and variable fate and transport behavior of energetic compounds (Corredor et al. 2024, Sharma et al. 2013).

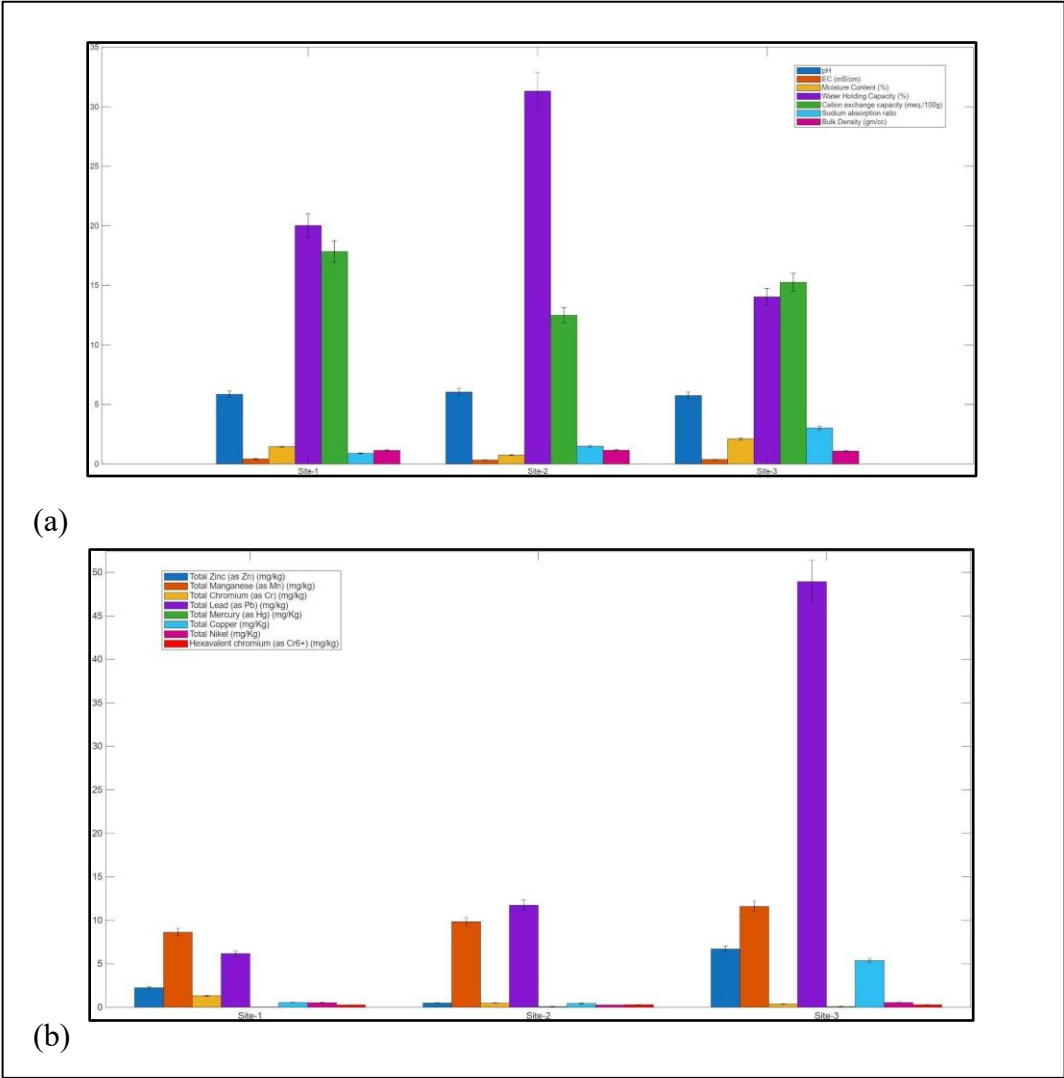


Fig 2: (a) Profile of soil physico-chemical parameters across the three study sites.

(b) Distribution of heavy metal contamination across the study sites.

Comparative analysis of soil physico-chemical parameters across the study sites (figure-2 (a)) revealed that all the three sites exhibited slightly acidic to near-neutral pH (5.75–6.05), indicating minimal alkaline influence from explosive residues. Electrical conductivity remained low across sites (0.34–0.43 mS/cm), suggesting limited salinity buildup. However, moisture content varied substantially. Sodium absorption ratio (SAR) was also highest in Site III (3.0), indicating potential sodicity concerns compared to blank soils. Bulk density was relatively consistent (1.085–1.15 g/cc), though slightly lower in Site III due to higher organic matter. Soil texture varied from sandy loam (Site I) to loamy sand (Site III), influencing water holding capacity, which was highest in Site II (31.30%) and lowest in Site III (14.04%).

Findings of heavy metal analysis (Figure-2 (b)) showed that Site III exhibiting significantly elevated levels of contamination by heavy metals especially Pb (48.93 mg/kg), Zn (6.70 mg/kg), and Cu (5.38 mg/kg), indicating accumulation from detonation residues and metallic components of explosives. Site II showed moderate Pb (11.73 mg/kg) and Hg (0.08 mg/kg), possibly linked to raw materials and process inputs. Chromium levels remained low across all sites, with negligible variation from background.

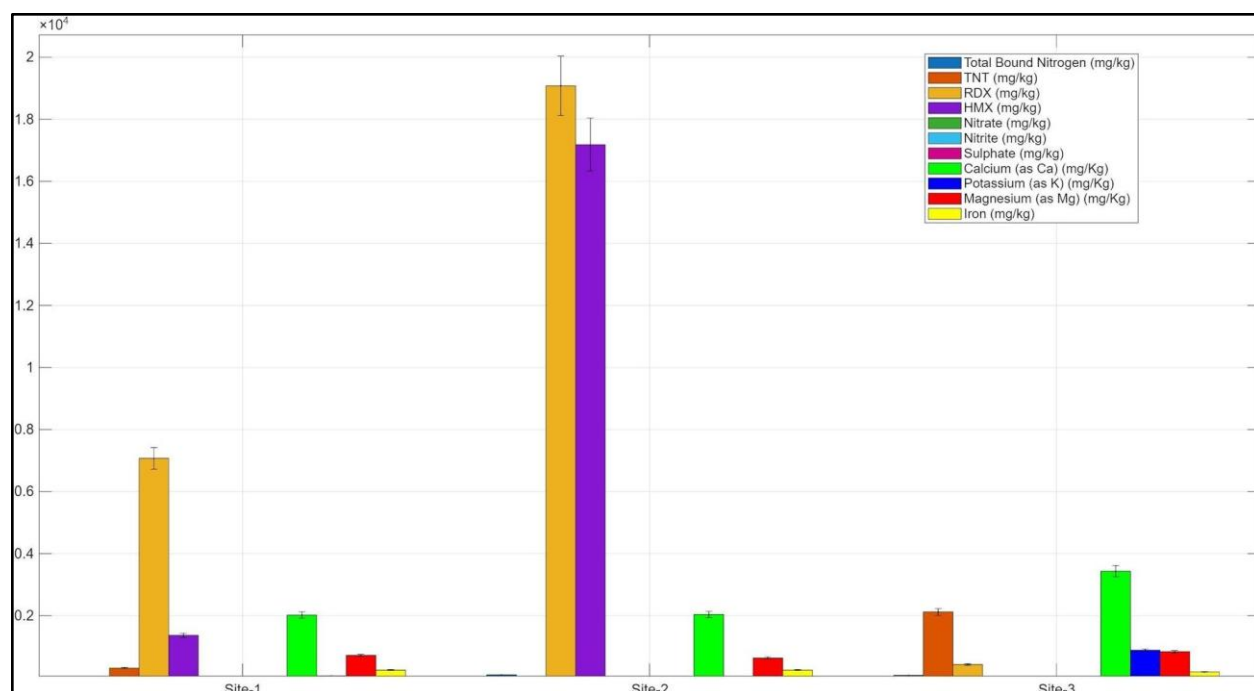


Fig 3: Trends in different nitrogen forms, high energy materials and ionic constituents in soil across the study sites.

Distribution of different nitrogen forms, levels of high energy materials and ionic constituents (Figure-3) varied across the sites. Site II (RDX–HMX manufacturing) showed elevated total bound nitrogen (98.35 mg/kg) and available nutrients, indicating accumulation of nitrogenous intermediates from manufacturing processes. Site I (machine cutting and washing activities) showed high RDX (7071.18 mg/kg) and moderate HMX (1370.77 mg/kg) along with detectable TNT, indicating mixed contamination from handling and washing operations. Site II exhibited the highest concentrations of RDX (19077.20 mg/kg) and HMX (17180.09 mg/kg), confirming it as a major point source of nitramine contamination due to manufacturing discharge (labyrinth sediments). Site III was dominated by TNT contamination (2122.32 mg/kg), consistent with incomplete detonation during open burning/open detonation (OB/OD) activities, while HMX was

absent. Site III showed elevated levels of Ca, K, and Mg, particularly potassium (889.07 mg/kg), reflecting ash deposition from explosive residues and combustion by-products.

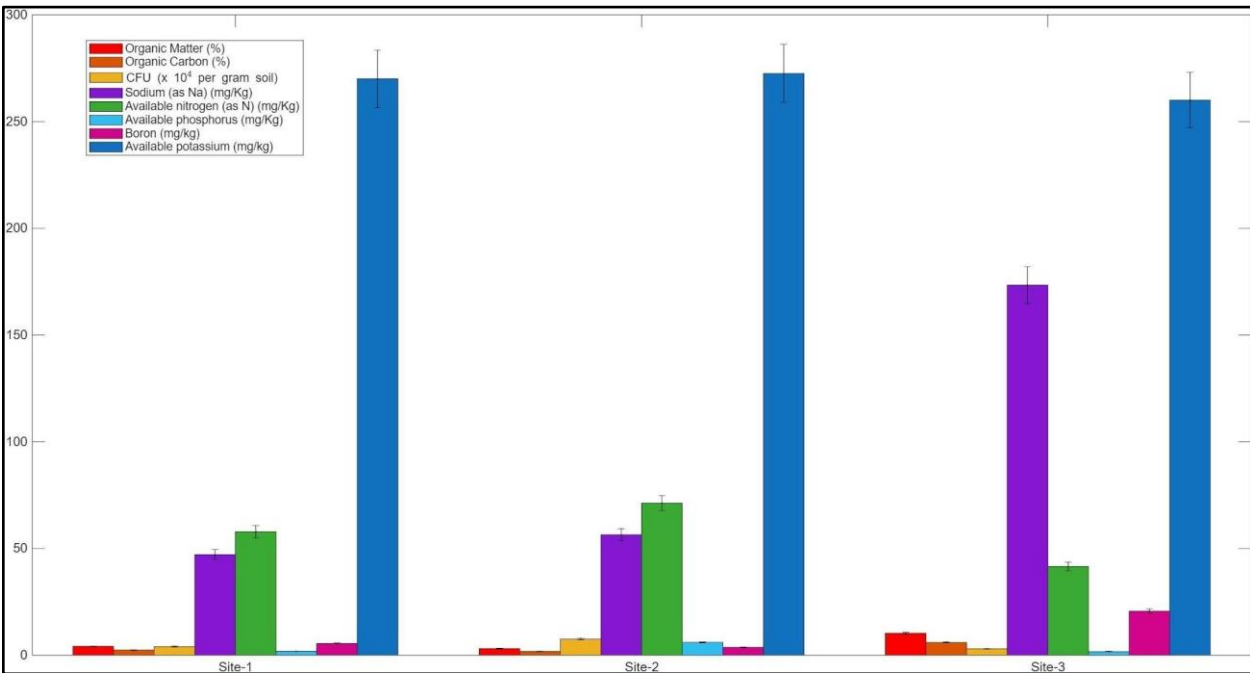


Fig 4: Distribution of soil quality parameters and microbial population across the studied sites

In contrast, Site III exhibited reduced available nitrogen (41.54 mg/Kg) despite high organic carbon, suggesting nutrient immobilization or loss due to thermal degradation during detonation events. Available phosphorus remained low across Sites I and III, comparable or slightly reduced. Organic matter varied substantially, with Site III (open burning/detonation) showing the highest organic matter (10.28%) and organic carbon (5.96%), likely due to incomplete combustion residues and deposition of soot and degraded organic fractions.

Assessment of soil quality parameters and microbial counts (Figure-4) in the study sites revealed that microbial count was the highest in Site II (8×10^4 CFU/g), likely due to acclimatization to nitrogen-rich substrates, whereas Site III showed significantly reduced microbial population (3×10^4 CFU/g), indicating toxicity and thermal stress effects from detonation processes. Site I showed moderate microbial activity. Site III showed elevated levels of sodium (173.38 mg/kg).

3.2.2 Development of SoQI and EQI

SoQI was calculated with 32 selected parameters from the total data set (Supplementary data). The scope, frequency and amplitude values calculated for SoQI of three sites is given below: SoQI of three military related activities in the study sites

	F1 Scope	F2 Frequency	Excursion	F3 Amplitude	SoQI
Site 1	50.00	43.55	26.60	96.38	32.5
Site 2	48.39	39.66	9.61	90.58	36.4
Site 3	61.29	48.33	4.16	80.62	35.2

Despite different kinds of military activities being conducted in the three study sites, SoQI classified all the three as high-concern categories pointing to environmental degradation. From the above result (F1 Scope), it is seen that more than 43% of contaminants did not meet their respective guidelines relative to the total number of contaminants at the site, in the case of all three sites. The same variation was observed for the F2 (frequency) of individual tests that do not meet their respective guidelines. Most parameters measured for site I (excursion: 26.58) did not meet the guidelines.

Interpretation of EQI values was guided by established soil quality index frameworks (Karlen et al. 1997; Andrews et al. 2004) and contamination factor classifications proposed by Hakanson (1980). Higher EQI values correspond to elevated contamination load relative to soil functional capacity and are associated with increasing ecological impairment. Correlation analysis was performed to identify the parameters to be considered for SFI and CLI calculations. Below given figure5 shows the correlation between different parameters

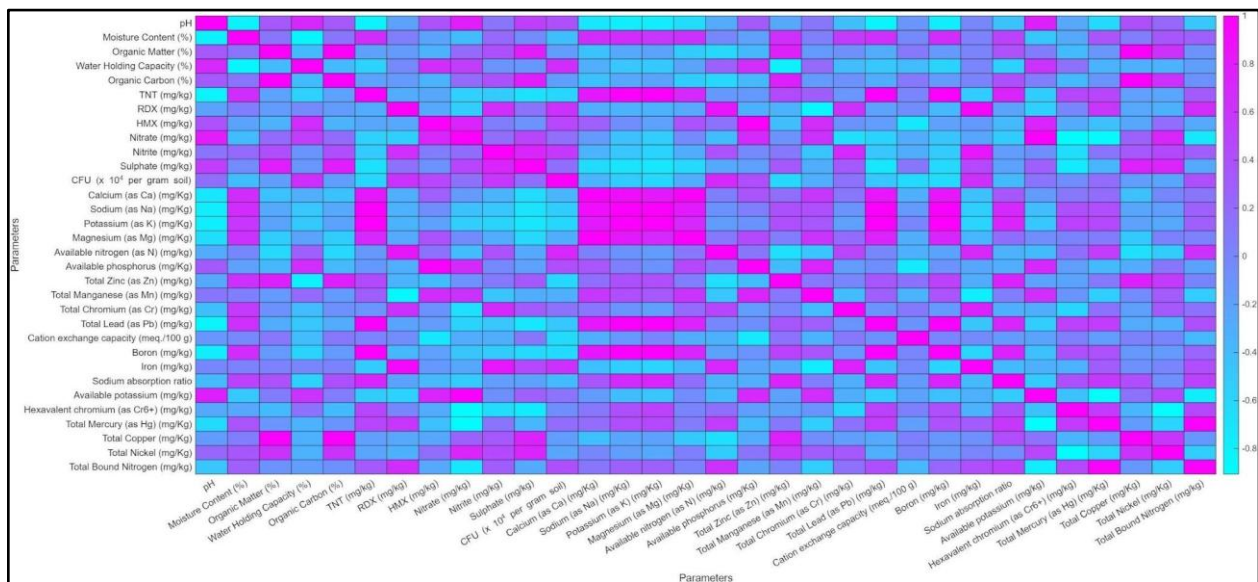


Fig 5. The correlation between different parameters analysed.

The correlation showed the strong correlation between explosives concentration and soil macro and micronutrients. Other parameters showing near to 0.9 were considered for calculation of EQI. Identified 11 polluting parameters were considered for CLI and 8 parameters were finalised for SFI. The calculated values for three different site is given below:

Soil Function Index (SFI), Contaminant Load Index (CLI) and EQI of three different sites.

SFI	CLI	EQI
-----	-----	-----

Site 1	0.92	18.49	11.46
Site 2	0.89	73.05	44.18
Site 3	0.86	5.2	3.47

496

497 The Environmental Quality Index (EQI) varied widely across the investigated sites, ranging from
 498 3.47 at SiteIII to 44.18 at Site II. EQI value at Site I (11.46) and Site III were driven by explosive
 499 residues, particularly TNT and RDX, indicating severe environmental degradation. Site II
 500 exhibited degraded EQI, reflected by the highest CLI (73.05) among the sites.

501

502 3.2.3 Plant and earthworm bioassay

503 Biological activity declined sharply with increasing EQI. Phytotoxic effects on wheat and green
 504 gram were assessed under soils with increasing EQI values. As EQI increased from 3 to 44,
 505 seedling emergence, shoot growth, biomass accumulation, and root elongation progressively
 506 declined. These trends are consistent with already reported findings showing inhibitory effects of
 507 explosives residues and co-contaminants on plant germination and early growth (Sunahara et al.
 508 2012; Beyer et al. 1996; OECD 208, 2006). While soils with EQI=3 exhibited moderate sub lethal
 509 stress to earthworms and partial inhibition of seed germination, sites with EQI ≥ 15 showed severe
 510 ecological impairment. At EQI =44, acute toxicity conditions were predicted, characterized by
 511 high earthworm mortality and substantial phytotoxicity in wheat and green gram, indicating
 512 ecosystem dysfunction.

513

514 3.2.4. Contaminant mobility

Significant variation in contaminant mobility were observed in the leachability assessment of explosive-contaminated soils from three sites. The vast majority of contaminants remain bound to the soil matrix, as demonstrated by the total proportion of leached compounds, which ranged from 0.08% to 3.08%. However, rather large leachate concentrations indicate a potential risk of groundwater contamination, particularly for RDX and HMX, TNT showed minimal leaching, but RDX and HMX showed the highest mobility among the explosives studied. Despite high soil concentrations, TNT leaching was minimal at site I, indicating considerable sorption. RDX (1.77%) and HMX (0.88)%, on the other hand, exhibited higher mobility; the depth-wise distribution displayed downward migration. Site -II exhibited the highest leachability particularly in samples collected from RDX plant wherein concentration increased with depth suggesting significant vertical transport under chronic hazardous circumstances. Both RDX (1.45%) and TNT (0.08%) demonstrated lower leachability at Site III, with higher concentrations confined to surface layers, implying little subsurface mobility. The observed mobility trend ($RDX > HMX > TNT$) is in conformity with their physicochemical characteristics, where TNT exhibits stronger sorption and transformation reactions that reduce its mobility, while increased solubility and lower sorption affinity of RDX improved its movement. The findings are consistent with previous studies conducted by Jenkins et al. (2001) and Pennington et al. (2002b), who observed considerable TNT retention and elevated RDX mobility in soils governed by both physico-chemical properties of the explosive compounds and the soil matrix.

4. Conclusion and recommendations

High levels of soil contamination by nitroaromatic and nitramine compounds were found in all the three high-energetic materials (HEM) handling depots in India. Peak concentrations for these

compounds amounted to 19,000 mg/Kg for RDX at Site II (manufacturing and transportation facility) and 17,180 mg/Kg for HMX at site III (waste disposal facility). While EQI varied from 3.47 to 44.18 moderate at site III to severely degraded at site II, driven by elevated CLI despite relatively resilient SFI. The SoQI values ranged from 33.6 to 36.3 across all locations placing them in ‘high concern category’. These findings were further supported by ecotoxicological tests which indicated that the phytotoxicity and stress to earthworm increased with decreasing EQI revealing poor environmental quality at high contamination areas. In addition, column leaching tests established RDX/HMX mobility risks (upto 3.08% leached) under simulated precipitation. Owing to high CLI values and the potential for vertical contaminant transport, these sites are identified as priority sites for implementation of appropriate remediation strategies. Based on these indices, a robust and integrative framework for HEM site assessment is recommended. Deployment of a permeable reactive barrier can reduce the contaminant leaching along with implementation of site-specific remediation strategy. To prevent further deposition, long term monitoring with EQI/CLI thresholds with operational limitations is recommended. Future research should investigate metagenomic drivers of microbial resilience as biological indicators along with physico-chemical characterization approaches and validate these indices across diverse climatic conditions and HEM types. Establishment and implementation of sustainable remediation strategies is essential for sustained restoration of former military sites. Thus an environmentally conscious approach can support effective management of HEM contaminated sites and ensure regulatory compliance.

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