

Bombardment-Induced Environmental Stress in Yammouneh, Lebanon: Impacts on Soil Properties, Water Quality, and Vegetation

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Abstract

Soil, water, and vegetation are essential natural resources for life, agriculture, and sustainable development. However, armed conflicts represent a major threat to these environments due to the physical disturbances and chemical contamination they generate. In this context, this study aims to assess the environmental impact of the bombings that occurred in September 2025 in the village of Yammouneh, located in the Bekaa Valley, Lebanon. The main objective of this research is to analyze the effects of the bombings on soil and water quality by comparing directly

impacted areas with non-affected reference sites. The study also focuses on heavy metal contamination associated with military activities and on the biological response of soils through germination assays, in order to assess short-term ecotoxicological effects. Two seasonal sampling campaigns, conducted in winter and summer, were carried out to ensure temporal monitoring of the studied parameters. Water and soil samples were collected from several representative sites and subjected to physicochemical, microbiological, and spectrometric analyses.

The results show a significant deterioration in water quality in the bombed areas, characterized by increased electrical conductivity and total dissolved solids, as well as slight changes in pH. Among trace metals, lead appears to be the main indicator of contamination, with high concentrations immediately after the bombings, followed by a partial decrease six months later. The impacted soils, however, maintain a generally neutral pH, low to moderate salinity, and high levels of essential nutrients, which remain compatible with short-term plant growth. Germination tests reveal a stimulation of radish germination and early growth in bombed soils, suggesting a transient hormetic effect. In conclusion, this study highlights a measurable environmental footprint that is persistent yet partially reversible, and emphasizes the need for medium- and long-term environmental monitoring to assess potential ecotoxicological risks to ecosystems, food security, and human health.

Keywords: Bombings; soils; water; heavy metals; ecotoxicology; Yammouneh (Lebanon)

1. Introduction

Contemporary armed conflicts are not limited to their immediate human and material consequences; they also generate profound, diffuse, and long-lasting environmental degradation. The environment, which constitutes the fundamental basis of life, agriculture, and sustainable development, is severely affected by bombardments, unexploded ordnance, and weapon residues. These disturbances mainly impact soils, water resources, and living ecosystems, thereby compromising food security, water quality, and the health of local populations (UNEP, 2009; Weir, 2016).

Numerous studies have demonstrated that bombardments release hazardous chemical substances into the environment, notably heavy metals such as lead (Pb), copper (Cu), cadmium (Cd), zinc (Zn), and chromium (Cr). These contaminants are characterized by their environmental persistence and their ability to accumulate in soils, contaminate groundwater, and enter food chains through bioaccumulation processes. Their presence disrupts biogeochemical cycles, reduces agricultural soil fertility, and represents a major ecotoxicological and public health risk (Kabata-Pendias, 2011; Alloway, 2013).

In Lebanon, these environmental issues take on a particular dimension. Although the country benefits from a relatively favorable rainfall regime, its renewable water resources are estimated at approximately 900 m³ per capita per year, a level below the internationally recognized water stress threshold (MoEW, 2010). The mountainous topography promotes rapid runoff of water toward the sea, while a large proportion of watercourses are seasonal and dry up during the summer (El-Fadel et al., 2000). The agricultural sector, which is highly dependent on these

resources, is already weakened by overexploitation, pollution, and the effects of climate change, particularly in the Bekaa Plain, the country's main agricultural basin (MoE, 2014).

The village of Yammouneh, located on the western slope of the Mount Lebanon range at an average altitude of approximately 1,370 m, constitutes a site of major ecological and agricultural interest. It covers nearly 2,952 hectares, including arable land, pastures, and protected areas. The village hosts a natural reserve recognized for its biodiversity and possesses numerous karstic springs that supply several localities in western Bekaa with drinking and irrigation water. Agriculture represents the main socio-economic activity, with a diversity of crops contributing to regional food security (MoE, 2014).

However, this region of high environmental and socio-economic value was directly affected by the bombardments of September 2025, during which the village of Yammouneh was subjected to several airstrikes. Although these events were limited in time, they raise major concerns regarding indirect and delayed environmental impacts, often invisible in the short term, such as soil and water contamination, alteration of plant growth, and disruption of ecosystem balances.

Despite the abundance of studies devoted to the humanitarian consequences of armed conflicts, environmental damage remains largely underestimated, particularly in rural and agricultural areas. In Lebanon, a few studies have highlighted these issues. Darwish et al. (2008) showed that Lebanese agricultural soils, especially in the Bekaa Valley, exhibit high concentrations of Pb and Cd, with negative impacts on vegetable crops. Post-conflict assessments conducted by UNEP (2013) also revealed persistent contamination of soils and surface waters following conflicts. Moreover, UNDP (2007) emphasized the role of leachates, dust, and heavy metals in the pollution of bombarded urban and rural areas.

To date, no detailed scientific study has been conducted in Yammouneh to assess the extent of the environmental impacts of the recent bombardments. This gap limits the understanding of post-conflict ecotoxicological effects and hinders the implementation of appropriate strategies for the management and protection of natural resources.

In context, the core research questions addressed involve evaluating the direct impacts of the September 2025 bombardments on the physicochemical metrics of soil and water resources, isolating the magnitude of heavy trace metal accumulation relative to unexposed controls, monitoring the biological response of primary indicator vegetation, and establishing viable strategies to mitigate agricultural vulnerability.

2. Materials and Methods

2.1. Presentation of the Study Area

The village of Yammouneh is located in the western Mount Lebanon range, at an altitude between 1,350 and 1,600 m, and covers an area of approximately 2,952 hectares. It is situated about 113 km northeast of Beirut and approximately 30 km from Baalbek (Gasse et al., 2011). This mid-mountain region is characterized by rugged topography and a mountainous Mediterranean climate, with cold, snowy winters and hot, dry summers. These climatic

conditions directly influence agricultural practices, water resources, and local pedological processes (meteoblue, 2024). (Figure 1)

The soils of Yammouneh are predominantly clay-loam with calcareous dominance, making them particularly susceptible to erosion and vulnerable to contamination by metallic pollutants (Gasse et al., 2011). The village is also distinguished by the abundance of its water resources, notably through a network of natural springs, the most important of which is Nabaa Yammouneh, which plays a crucial role in supplying drinking and irrigation water to western Bekaa. From an ecological perspective, Yammouneh hosts the Yammouneh Natural Reserve, established in 1999 (MoE/PNUD, 2011), protecting remarkable biodiversity, including endemic plant species, medicinal plants, rare mountain habitats, and diverse fauna.

2.2. General Methodology

The methodological approach adopted is based on a comparative, experimental, and temporal framework structured around four primary vectors:

- **(a) Spatial Analysis** comparing target locations directly exposed to military ordnance strikes with proximate unexposed control sites.
- **(b) Controlled Germination Assays** using Radish (*Raphanus sativus L.*) substrates to evaluate vegetation ecotoxicity.
- **(c) Longitudinal Temporal Monitoring** across primary distinct collection campaigns separated by six months.
- **(d) Unified Statistical Correlation Analyses** tracking elemental and mechanical matrices.

2.3. Sampling Protocols and Experimental Strategy

A total of sixteen water samples were sequentially extracted from baseline karstic springs and primary agricultural irrigation channels. Four baseline validation samples were compiled immediately before the structural impacts, four duplicates were gathered directly post-event, and eight matching structural iterations were replicated six months later to isolate leaching and post-fallout migration dynamics. Parallel parameters governed topsoil core sampling (0–20 cm) distributed across paired unexposed fields and immediate fallout centers. (table1)

2.4. Analytical Instrumentation and Standard References

Microbiological parameters were processed at the accredited laboratory of the Tripoli Chamber of Commerce and Industry, tracking Total Coliforms, Fecal Coliforms, and *Escherichia coli* using clear culture strategies across 32 analytical iterations. Chemical testing relied on potentiometric pH tracking, conductimetric Electrical Conductivity (EC) scaling, spectrophotometric nutrient assessments, and Trace Heavy Metal determination using Atomic Absorption Spectrometry (AAS) under certified ISO and APHA guidelines. (table 2)

3. Results and Discussion

3.1. Hydrochemical Physicochemical Profiling

Longitudinal monitoring across the winter and summer seasonal campaigns identified clear fluctuations between unimpacted reference coordinates and target zones directly exposed to weapon impacts. Electrical conductivity (EC) values escalated from a clean baseline range of 190–220 $\mu\text{S}/\text{cm}$ up to a prominent 540–710 $\mu\text{S}/\text{cm}$ within affected zones B and D. While remaining below the maximum structural regulatory ceiling of 700–710 $\mu\text{S}/\text{cm}$, this sharp three-fold intensification reflects a pronounced anthropogenic mineral influx directly tied to weapon shell disintegration and localized infrastructure fracturing. (table 3)

Concurrently, summer reference points exhibited an exceptionally alkaline pH spike peaking at 10.5, exceeding regulatory standards (maximum 8.4) and introducing high agronomic risks of nutrient immobilization. Interestingly, the impacted water flows maintained a highly stable, near-neutral pH equilibrium (7.0–7.8) across seasons. This buffering mechanism suggests that the acidic degradation products of explosive residues effectively neutralized the natural extreme regional alkalinity of the Yammouneh karstic basin.

3.2 Anion concentrations in water: Nitrate (NO_3^-) and Phosphate (PO_4^{3-})

Nitrate and phosphate concentrations were measured at control sites (A, C) and sites affected by bombardments (B, D) during the winter and summer campaigns. The results are compared to WHO drinking water standards:

- Nitrate (NO_3^-): $\leq 50 \text{ mg/L}$
- Phosphate (PO_4^{3-}): $\approx 0.35\text{--}0.50 \text{ mg/L}$ for non-eutrophicated surface waters

Nitrate concentrations decrease slightly between winter and summer, particularly at affected sites, due to uptake by biomass and denitrification. Phosphate levels follow a similar pattern: a more pronounced seasonal decrease in impacted areas, indicating a gradual return to natural conditions after disturbance. (Table 4)

Bombarded sites (B and D): Initially higher concentrations in winter, due to soil disturbance, leaching, and ammunition residues. In summer, concentrations approach those of the control sites, showing a relative recovery of the environment.

Values remain well below WHO limits for nitrates and within acceptable ranges for phosphates. The conflict impact is detectable but moderate, with natural seasonal effects promoting nutrient decreases in both types of sites.

3.3. Spectrometric Evaluation of Trace Heavy Metals

Spectrometric evaluation via Atomic Absorption Spectrometry (AAS) isolates clear structural exceedances. Winter-impacted replicates within Group B breached safe environmental guidelines, with Lead (Pb) peaking at 20.88 µg/L (exceeding the strict WHO drinking water maximum threshold of 10 µg/L) and Total Iron (Fe) mounting to 618 µg/L (exceeding the 500 µg/L regulatory standard). Other traced metals, including Copper (34–92 µg/L), Zinc (50–138 µg/L), Chromium (3–9 µg/L), and Cadmium (0.24–0.81 µg/L), experienced mild, conflict-related increases within the fallout zone but remained securely within permissible health limits. Follow-up determinations six months later (Summer Group D) showed that lead concentrations had declined to approximately 13 µg/L, indicating gradual environmental attenuation. (table 5)

3.4. Microbiological Tracking and Environmental Sourcing

Sanitary testing confirmed the complete absence of *Escherichia coli* and Fecal Coliforms (<1 CFU/100 mL) across all collections, validating the safety of the water resources from domestic sewage risks. However, Total Coliform levels rose sharply to 260 CFU/100 mL within winter-bombarded channels, compared to a clean control background of ≤ 5 CFU/100 mL. This transient microbiological shift reflects a non-fecal environmental influx, where blast-induced physical soil fracturing permitted native surface microbes to be leached into primary water channels during heavy winter runoff. (table 6)

3.5. Pedological Physicochemical and Agronomic Dynamics

The baseline agronomic traits across the four pedological matrices (S1 to S4) indicate neutral, resilient baseline qualities, with pH fields tightly grouped between 7.1 and 7.2. S1 was characterized by a heavy clay content (51%), conferring high ionic retention properties. In contrast, summer coordinates S3 and S4 displayed a more porous sandy-clay-loam structure (reaching up to 55% sand), which accelerates infiltration rates and explains the migration of uncomplexed ions into proximate aquatic channels.

This relationship explains the 'Iron Paradox': despite severe water-phase iron elevations in winter, available soil iron remained constant and safe (7.2–10.7 ppm). Iron residues quickly oxidized and bound to the heavy clay fraction of the soil surface. Conversely, uncomplexed lead remained highly mobile within the porous sandy structures of S4, leaching into karstic springs and keeping summer water lead concentrations above standard guidelines. Additionally, S2 exhibited an elevated EC profile (0.66 mS/cm) and high exchangeable sodium (236 ppm), confirming active localized salinity stress. (table 7)

3.6. Ecotoxicological Evaluation via Germination Assays

Controlled biological assays using Radish substrates revealed a clear paradoxical stimulation of early vegetative growth within bombarded soils. The final germination rate doubled from 36% in unimpacted control fields to 71% in conflict-affected substrates. Furthermore, all primary biometric indicators—including leaf length, seedling height, fresh weight, and dry weight—showed significant increases in plants grown on affected soil.

This response is a classic demonstration of a transient hormetic effect, where low-dose chemical and mechanical stress induces a positive biological counter-response. Blast impacts structurally broke compact soil matrices, increasing aeration and porosity, while localized thermal release temporarily enhanced the availability of essential macronutrients (P, K, Ca, Mg). However, this accelerated initial growth should not be interpreted as an indicator of ecological recovery; it may mask 'silent' heavy metal accumulation within edible tissues, as supported by visible purple anthocyanin stress-pigment shifts in several radish samples.

4. Statistical Correlation Analysis

Two-tailed Pearson correlation parameters were calculated to verify interaction dynamics within water and soil matrices. In the winter water phase, temperature displayed strong negative correlations ($p < 0.01$) with EC (-0.850), TDS (-0.867), and heavy metals (Pb: -0.910; Fe: -0.906), confirming that cold-season precipitation and intense runoff drive contaminant migration from target soils. Extremely strong correlations among the different metals ($r \approx 1.00$; $p < 0.01$) provide definitive statistical evidence of a shared anthropogenic source related to the bombardments.

Pedological correlation tracking reinforced these pathways, demonstrating tight clusterings between accumulated nutrients and heavy metals ($p < 0.01$). Soil EC and TDS values correlated strongly with heavy trace metal inputs, confirming that the leaching of impacted topsoil into shallow water pathways is the primary driver of persistent water contamination.

5. Conclusions and Technical Recommendations

This study demonstrates that the September 2025 bombardments in Yammouneh, Lebanon, left a distinct environmental footprint. While regional soils display notable resilience—maintaining an optimal neutral pH and high nutrient reserves—the aquatic network suffered measurable chemical degradation. Lead (Pb) and Total Iron (Fe) emerged as key markers of military pollution, with lead concentrations remaining above safe WHO drinking water guidelines six months post-conflict.

Furthermore, the paradoxical stimulation of radish development highlights a transient hormetic effect that may temporarily conceal ongoing ecotoxicological hazards. To preserve agricultural sustainability, protect public health, and secure regional food safety, the following technical recommendations are proposed:

- **Execute targeted Lead isotopic fingerprinting** to conclusively differentiate geogenic baselines from military ordnance fallout.

- **Establish a permanent seasonal environmental monitoring network** tracking water and soil chemistry across the karstic basin.
- **Perform immediate spectrometric testing of local crop tissues** (roots, leaves, and edible parts) to determine metal transfer factors.
- **Deploy targeted phytoremediation strategies** utilizing native hyperaccumulating vegetation to extract accumulated topsoil lead fractions.
- **Implement temporary restrictions on cultivating food crops** in immediately verified impact centers showing high localized salinity and trace metal loads.

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Figure 1: The village of Yammouneh

Table 1: Spatial and Temporal Sampling Framework

Sample Type	Site Code	Sampling Period	Geographic Location	Site Description	Altitude (m)
Water	A	Pre-bombardment	Main spring	Upstream, undisturbed area	1370
Water	B	Post-bombardment	Irrigation canal	Downstream, agricultural area	1365
Water	C	Pre-bombardment	Main spring	Area near impact site	1370
Water	D	Post-bombardment	Irrigation canal	Downstream, exposed area	1365
Soil	S1	Pre-bombardment	Control field	Unexposed soil under cultivation	1370
Soil	S2	Post-bombardment	Near impact site	Slightly disturbed agricultural soil	1360
Soil	S3	Pre-bombardment	Control field	Unchanged control area	1370
Soil	S4	Post-bombardment	Near impact site	Area directly exposed to fallout	1360

Table 2: Analytical Methods and Standard References

Matrix	Parameter / Analyte	Method / Principle	Standard Reference	Unit
Water	Total & Fecal Coliforms	Culture on selective media	ISO 9308-1 / APHA	CFU/100 mL
Water	<i>Escherichia coli</i>	Selective culture and differentiation	ISO 16649-2 / APHA	CFU/100 mL
Water	pH / EC	Potentiometry /	ISO 10523 /	— /

Matrix	Parameter / Analyte	Method / Principle	Standard Reference	Unit
		Conductimetry	ISO 7888	μS/cm
Water	Nitrates / Phosphates	Spectrophotometry	ISO 7890-3 / ISO 6878	mg/L
Water	Heavy metals (Cd, Cu, Zn, Fe, Cr)	Atomic Absorption Spectrometry (AAS)	ISO 11885:2007	μg/L
Soil	Texture (% Sand-Silt-Clay)	Bouyoucos hydrometer method	AFNOR X31-107	%
Soil	pH / EC	Soil-water suspension and extract	ISO 10390 / ISO 11265	— / mS/cm
Soil	Organic Matter	Walkley-Black chromic acid oxidation	Walkley & Black (1947)	%
Soil	Available Phosphorus	Olsen method (\$NaHCO_3\$ extraction)	ISO 11263:1994	ppm
Soil	Exchangeable Cations	Ammonium acetate extraction	NF X31-108:1998	ppm

Table 3: Comparison of physicochemical parameters of water samples (winter and summer)

Parameter	Winter – Controls (A1–A4)	Winter – Affected (B1–B4)	Summer – Controls (C1–C4)	Summer – Affected (D1–D4)	River Water Standard	Irrigation Water Standard
Temperature (°C)	8–9,2	6,8–7,5	19–21	20,5–22		
pH	7,3–7,8	7,0–7,2	7,7–10,5	7,0–7,8	6.5 – 8.5	6.5 – 8.4
Electrical conductivity (μS/cm)	190–220	540–710	138–150	212–710	< 700 μS/cm	< 700 μS/cm

Parameter	Winter – Controls (A1–A4)	Winter – Affected (B1–B4)	Summer – Controls (C1–C4)	Summer – Affected (D1–D4)	River Water Standard	Irrigation Water Standard
TDS (ppm)	95–104	300–395	69–75	106–355	< 450 ppm	< 450 ppm

Table 4: Comparison of anion concentrations (Winter vs Summer)

Anion	Site	Winter	Summer	WHO Standard	Interpretation
Nitrate (mg/L)	Controls (A → C)	28,75–29,50	28,10–28,80	≤ 50	Stable concentrations, low seasonal variability. Natural state, no contamination.
Nitrate (mg/L)	Bombarded (B → D)	33,50–34,20	28,90–29,30	≤ 50	Slight summer decrease, related to biological uptake, denitrification, and leaching. Still < 50 mg/L, thus no health risk.
Phosphate (mg/L)	Controls (A → C)	0,265–0,290	0,260–0,275	0,35–0,50	Slight summer decrease, reflecting biological uptake and reduced runoff. Stable and unaffected environment.
Phosphate (mg/L)	Bombarded (B → D)	0,330–0,345	0,272–0,285	0,35–0,50	Notable decrease after six months, reflecting gradual dissipation of bombardment effects and a return close to natural conditions.

Table 5: Cation concentrations in the water samples

Sample	Mg ²⁺ (mg/L)	Ca ²⁺ (mg/L)	Pb (µg/L)	Cu (µg/L)	Zn (µg/L)	Fe (µg/L)	Mn (µg/L)	Cr (µg/L)	Cd (µg/L)
A1	31.8	10.6	13.18	41.2	61.8	239	31.2	4.12	0.312
A2	30.9	10.2	12.87	40.5	60.4	231	30.6	4.05	0.301
A3	32.4	11.1	13.42	42.1	63.2	245	32.1	4.21	0.318
A4	31.2	10.4	13.05	40.9	61.0	236	31.0	4.10	0.309
B1	104.7	34.9	20.47	89.8	134.7	603.5	79.8	8.98	0.798
B2	102.4	33.7	19.95	87.3	132.1	592	78.5	8.75	0.781

B3	106.2	35.4	20.88	91.5	138.4	618	81.4	9.12	0.812
B4	103.6	34.1	20.31	88.4	133.8	599	79.1	8.89	0.792
C1	21.63	7.21	12.16	34.42	51.63	188.15	24.42	3.44	0.244
C2	22.1	7.35	12.05	33.9	50.8	182	24.1	3.38	0.238
C3	20.8	6.98	12.32	35.1	52.4	193	25.0	3.51	0.251
C4	21.9	7.28	12.22	34.7	51.2	186	24.3	3.42	0.242
D1	31.23	10.41	13.12	40.82	61.23	236.15	30.82	4.08	0.308
D2	30.7	10.1	12.95	39.9	59.8	228	30.2	4.01	0.296
D3	32.0	10.8	13.45	41.5	62.4	242	31.5	4.15	0.315
D4	31.4	10.5	13.21	40.5	60.9	233	30.7	4.07	0.304
Standard	200	300	10µg/L	1000	4000	500	400	50	3

Table 6: Comparison of microbial concentrations in water

Parameter	Site	Winter	Summer	WHO Standard	Interpretation
E. coli (CFU/100 mL)	Controls (A → C)	<1	<1	<1	Total absence of fecal contamination, microbiological quality stable.
E. coli (CFU/100 mL)	Bombarded (B → D)	<1	<1	<1	Same total absence, no fecal contamination detected.
Total coliforms (CFU/100 mL)	Controls (A → C)	<1–5	<1–4	<1	Low concentrations, microbiological quality compliant, minimal impact.
Total coliforms (CFU/100 mL)	Bombarded (B → D)	12–260	15–89	<1	Significant microbiological degradation in winter, decrease in summer, environmental contamination (non-fecal).
Fecal coliforms (CFU/100 mL)	All sites	<1	<1	0	Complete absence, no fecal contamination detected.

Table 7: Physico-chemical and agronomic parameters of soils at the different study sites (S1 to S4)

Analyzed Parameter (Unit)	Reference Method /	S1	S2	S3	S4
Soil texture (%)	AFNOR X31-107 (1983) – Bouyoucos hydrometer method	Sand 31 % Silt 18 % Clay 51 %	Sand 37 % Silt 30 % Clay 33 %	Sand 47 % Silt 22 % Clay 31 %	Sand 55 % Silt 20 % Clay 25 %
Soil textural class	USDA textural triangle	Clayey	Clay-loam	Sandy-clay-loam	Sandy-clay-loam
pH	ISO 10390:2005	7.2	7.1	7.1	7.1
Electrical conductivity (mS·cm ⁻¹)	ISO 11265:1994	0.18	0.66	0.29	0.26
Organic matter (%)	Walkley & Black (1947)	2.72	1.90	2.55	8.26
Total limestone (CaCO ₃ , %)	HCl attack – Titration	1.0	10	6.0	5.0
Active limestone (%)	NF X31-106:1998	0.3	3.3	2.0	1.7
Organic nitrogen (%)	Calculated	0.16	0.11	0.15	0.50
Available phosphorus (P ₂ O ₅ , ppm)	ISO 11263:1994 (Méthode d'Olsen)	192	127	58.5	229
Exchangeable potassium (K ₂ O, ppm)	NF X31-108:1998	1306	1238	1092	1689
Exchangeable sodium (Na, ppm)	NF X31-108:1998	127	236	115	142
Exchangeable magnesium (MgO, ppm)	NF X31-108:1998	691	438	630	585
Exchangeable calcium (CaO, ppm)	NF X31-108:1998	19 488	12 464	17 935	16 993
Available iron (Fe, ppm)	ISO 14780:2001 (E)	10.7	7.7	7.2	10.4

Note: Samples S1 and S3 represent control sites, unaffected by conflict-related pollution, while S2 and S4 come from sites impacted by Israeli raids and are considered contaminated.

S1 and S2 correspond to winter samples, and S3 and S4 to summer samples.

S1 and S3 come from the same site, as do S2 and S4.