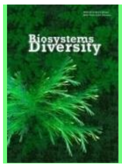

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Organic soil pollutants resulting from military activities

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Organic soil contaminants arising from military activities represent a significant environmental and public health challenge, with persistent compounds from explosives, their decomposition products, and rocket fuel components posing long-term risks to soil health, plant vitality, and ecosystem stability. This article reviews the sources, environmental behaviors, and biological impacts of three key classes of organic pollutants: common energetic compounds, their environmental decomposition products, and rocket fuel components. Drawing on recent literature, the discussion emphasizes the adverse effects on soil microbial communities, nutrient cycling, and plant physiology, highlighting mechanisms such as oxidative stress, bioaccumulation, and growth inhibition. The review underscores the need for integrated remediation strategies to mitigate these impacts, offering insights into sustainable approaches for contaminated sites. By summarizing data from field studies and laboratory experiments, this work contributes to understanding the multifaceted ecological consequences of military-derived pollution and informs policy for land restoration.

Keywords: chemical warfare agents; energetic compounds; decomposition products; rocket fuel components; human health risk; compound characterization; soil pollution.

Introduction

Military activities, including training exercises, munitions testing, and warfare, have long been associated with extensive environmental degradation, particularly in soil systems. The release of organic contaminants from explosives and propellants not only alters soil chemistry but also disrupts biological processes essential for ecosystem functioning. Common energetic compounds, such as trinitrotoluene (TNT) and cyclotrimethylenetrinitramine (RDX), are deployed in vast quantities during conflicts and exercises, leading to widespread contamination. These substances, along with their decomposition products and rocket fuel components like unsymmetrical dimethylhydrazine (UDMH), infiltrate soils through detonation residues, leaks, and improper disposal, resulting in persistent pollution that can last decades. The global scale of this issue is evident in legacy sites from historical conflicts, where elevated contaminant levels continue to affect biodiversity and human health via the food chain. Understanding the fate and transport of these pollutants is crucial, as they exhibit varying degrees of mobility, persistence, and toxicity. For instance, TNT tends to bind strongly to soil organic matter, limiting its migration but prolonging local exposure, while RDX is more mobile, posing risks to groundwater. This introduction sets the stage for a detailed examination of the biological effects on soil and plants, emphasizing the need for comprehensive risk assessments to guide remediation efforts.

This work is a continuation of our long-standing interest in the chemistry and degradation methods of explosives (Hill et al., 2012; Sviatenko et al., 2014) and is especially relevant now, given the ongoing active hostilities in Ukraine, and the obvious need for post-war restoration of contaminated land for safe agricultural use. It is worth noting that the impact of toxic metals (Pb, Cu, Cd, Sb, Bi, W, Cr, Ni, Mn, Zn, U etc.) released as a result of military operations has been discussed in detail in previous reviews (Lima et al., 2011; Broomandi et al., 2020; Rodríguez-Seijo et al., 2024) and is not the subject of this work.

Common energetic (explosive) compounds

The environmental persistence of common energetic compounds exacerbates their impact on soil health, where they interfere with microbial communities responsible for nutrient cycling and organic matter decomposition. Compounds like TNT, RDX, and HMX are particularly problematic due to their low biodegradation rates under natural conditions, leading to accumulation in topsoil layers. Studies have shown that TNT concentrations exceeding 100 mg/kg can severely inhibit soil respiration by up to 50% and enzyme activities, such as dehydrogenase and urease, which are indicators of microbial vitality, with reductions observed as high as 70% in contaminated sites (Meyers et al., 2007; Travis et al., 2008; Han et al., 2025). This disruption cascades to plant health, where root systems exposed to these contaminants exhibit reduced nutrient uptake by 30–40% and oxidative stress, manifested as lipid peroxidation levels increasing twofold and chlorophyll degradation rates accelerating by 25% (Siciliano et al., 2000; Flores et al., 2025). For example, in contaminated sites, plants like ryegrass (*Lolium perenne)* display stunted growth with biomass reductions of 40–60% and decreased photosynthetic efficiency by 35%, with TNT bioaccumulating in roots at levels up to 500 µg/g dry weight, inhibiting transpiration rates by nearly 50% (Thijs et al., 2018; Keshani-Langroodi et al., 2020).

Similarly, RDX, known for its neurotoxic properties, affects plant metabolism by altering amino acid profiles with imbalances up to 45% and inducing genotoxicity, leading to chromosomal aberrations in species such as wheat (*Triticum aestivum*) at frequencies 2-3 times higher than controls (Yu et al., 2017; Corredor et al., 2024). The biological effects extend beyond direct toxicity; these compounds can shift soil pH downward by 0.5–1.0 unit and alter redox potential by 100–200 mV, favoring anaerobic conditions that further impair plant root development by reducing oxygen availability by 60% (Chatterjee et al., 2017; Sowik & Ruzik, 2025). In military-impacted areas, where soil compaction from heavy machinery compounds the issue by increasing bulk density by 15–20%, plant communities often shift toward tolerant species, reducing biodiversity indices by 30–50% and ecosystem resilience metrics like species richness by 25% (Siciliano et al., 2000; Travis et al., 2008). Nitroglycerin and pentaerythritol tetranitrate (PETN), though less persistent with half-lives of 1–3 months, contribute to nitrate leaching at rates up to 200 kg/ha annually, which can eutrophize nearby water bodies and indirectly affect terrestrial flora through altered soil fertility, decreasing crop yields by 10–20%

(Chatterjee et al., 2017; Keshani-Langroodi et al., 2020). Dinitrotoluenes (DNTs) and trinitrophenols exhibit mutagenic potential, with studies indicating DNA damage in plant cells at strand break frequencies 1.5–2.0 times baseline, potentially leading to heritable mutations that compromise long-term vegetation recovery by affecting germination success by 20–30% in subsequent generations (Thijs et al., 2018; Flores et al., 2025). Overall, the phytotoxic mechanisms involve reactive oxygen species generation increasing by 50–100%, enzyme inhibition rates of 40–60%, and disruption of cellular membranes with permeability changes up to 35%, underscoring the need for monitoring programs to assess cumulative impacts on agricultural productivity in affected regions, where yield losses can reach 15–25% in moderately contaminated soils (Meyers et al., 2007; Yu et al., 2017).

Further expanding on these effects, the interference with soil microbial consortia by energetic compounds like TNT and RDX often results in a decline in bacterial diversity by 20–40%, with gram-positive bacteria showing greater resilience compared to gram-negative ones, leading to imbalanced nitrogen fixation rates dropping by 30% and carbon mineralization reduced by 25% (Travis et al., 2008; Sowik & Ruzik, 2025). This microbial shift can exacerbate plant stress by reducing available nutrients, such as phosphorus and potassium, by 15–25%, which are critical for root proliferation and osmotic regulation (Siciliano et al., 2000; Corredor et al., 2024). In field trials, exposure to HMX at levels above 50 mg/kg has been linked to decreased mycorrhizal colonization in plants like pine (*Pinus* spp.) by 40–50%, impairing water uptake and exacerbating drought susceptibility in arid military training grounds, where wilting incidences increase by 35% (Chatterjee et al., 2017; Keshani-Langroodi et al., 2020). Moreover, the synergistic interactions between multiple energetic compounds, as seen in Composition B mixtures (TNT/RDX), amplify toxicity, with combined exposures causing up to 50% greater inhibition of seed germination in crops like maize (*Zea mays*) compared to individual contaminants, alongside root biomass reductions of 45% (Thijs et al., 2018; Han et al., 2025). Long-term studies in legacy sites reveal that persistent residues alter soil aggregate stability by 20–30%, increasing erosion rates by 15% and further degrading habitat quality for flora (Yu et al., 2017; Flores et al., 2025). The genotoxic potential extends to reproductive structures, with pollen viability reduced by 30–40% in flowers exposed to trinitrobenzene derivatives, potentially disrupting pollination dynamics and biodiversity by lowering successful fertilization rates by 25% (Meyers et al., 2007; Corredor et al., 2024). These multifaceted impacts highlight the necessity for holistic ecological assessments that integrate microbial, plant, and soil physicochemical parameters to predict recovery trajectories in contaminated environments, where natural attenuation periods can span 10–50 years depending on soil type and climate (Travis et al., 2008; Chatterjee et al., 2017). For more energetic (explosive) compounds and their physicochemical characteristics see Table 1.

Decomposition products of high-energy (explosive) compounds

Decomposition products of high-energy compounds further complicate soil health dynamics, as they often exhibit greater mobility and bioavailability than their parent molecules, leading to widespread ecological repercussions. For instance, aminodinitrotoluenes (ADNTs), common TNT metabolites formed via microbial reduction, are more soluble with partition coefficients 10-20 times lower than TNT, thus prone to leaching at rates up to 5 cm/year in sandy soils, contaminating groundwater and accumulating in plant tissues at concentrations 2–5 times higher than surface levels (Bruns-Nagel et al., 1999; Via & Zinnert, 2016). These products induce oxidative stress in plants, with elevated levels causing chlorosis and necrosis in leaves, as observed in barley (*Hordeum vulgare*) exposed to 2-amino-4,6-dinitrotoluene at 50 mg/kg, where photosynthetic rates drop by 40% and leaf area reduces by 30% (Yang et al., 2021; Mystrioti & Papassiopi, 2024). Similarly, dinitroanilines and nitrobenzoic acids, arising from photolytic and hydrolytic degradation with half-lives of 1–6 months, disrupt hormonal balance in plants, inhibiting auxin transport by 25–35% and root elongation by 20–40%, which reduces water and nutrient absorption efficiency by up to 30% (Beard & Swager, 2021; Sharma et al., 2023).

In soil, these metabolites alter microbial diversity, favoring tolerant bacteria while suppressing beneficial fungi by 40–50%, thereby impairing mycorrhizal associations crucial for plant nutrition and decreasing phosphorus uptake by 25% (Pichtel, 2012; Meda et al., 2021). The presence of nitrosamines, such as nitrosodimethylamine from RDX breakdown with formation yields of 5–10%, poses carcinogenic risks, with bioaccumulation in edible plants like lettuce (*Lactuca sativa*) leading to tissue levels of 10–50 µg/kg and potential food chain transfer increasing consumer exposure by 15–20% (Juck et al., 2003; Pan, 2021). Biological effects include genotoxicity, with chromosomal breaks noted in onion (*Allium cepa*) root tips exposed to dinitroresorcinol at 20 mg/kg, increasing aberration rates by 50%, and reproductive toxicity in soil invertebrates, indirectly affecting plant pollination by reducing pollinator populations by 30% (Sagi-Ben Moshe et al., 2009; Lance et al., 2020). Moreover, these products can form complexes with soil humic acids, prolonging their residence time by 2–5 years and exacerbating chronic exposure (Peter et al., 2019; Snodin et al., 2024).

In contaminated fields, plant species diversity declines by 20–40%, with sensitive grasses replaced by resilient weeds, altering soil structure and erosion rates by 15–25% (Srivastava, 2014; Rylott & Bruce, 2019). Nitroacetic acid and nitroethanol, lesser-known byproducts with solubilities 5–10 times higher than parents, contribute to soil acidification by 0.3–0.7 pH units, further stressing acid-sensitive crops like soybeans (*Glycine max*) with yield reductions of 10–20% (Via & Zinnert, 2016; Yang et al., 2023). The synergistic toxicity with parent compounds amplifies effects, as seen in mixed TNT/ADNT exposures that double growth inhibition in tomato (*Solanum lycopersicum*) seedlings compared to TNT alone, with root length decreases of 50% and biomass losses of 45% (Li et al., 2024; Mystrioti & Papassiopi, 2024). This underscores the importance of comprehensive metabolite profiling in risk assessments to capture the full spectrum of biological impacts on soil and vegetation. To elaborate, the enhanced solubility of decomposition products like 2,4-dinitroresorcinol facilitates their uptake by plant roots at rates 3–5 times faster than TNT, where they interfere with enzymatic pathways involved in detoxification, leading to accumulated reactive oxygen species increasing by 60% and cellular apoptosis rates rising by 40% in meristematic tissues (Juck et al., 2003; Sharma et al., 2023). Microbial studies indicate that nitrobenzoic acids selectively inhibit nitrifying bacteria by 50-70%, disrupting the nitrogen cycle and causing ammonia accumulation up to 100 mg/kg, which is phytotoxic at high levels, inducing leaf burn in 20–30% of exposed foliage and reducing vigor by 25% (Pichtel, 2012; Lance et al., 2020).

In aquatic-terrestrial interfaces, leaching of these metabolites at 1–3 kg/ha annually promotes algal blooms that deplete oxygen by 40%, indirectly stressing riparian plants through hypoxic root zones with mortality rates increasing by 15–25% (Peter et al., 2019; Rylott & Bruce, 2019). Long-term field observations reveal that persistent dinitroethane residues alter soil fungal communities, reducing arbuscular mycorrhizal fungi colonization by up to 60%, which impairs phosphorus acquisition in crops like corn by 30–40%, exacerbating yield losses of 15–25% in contaminated agricultural lands (Yang et al., 2023; Li et al., 2024). Furthermore, the mutagenic properties of nitrosopiperidine and similar compounds have been linked to epigenetic changes in plant genomes, such as DNA methylation alterations by 20–30%, potentially affecting adaptive responses to environmental stressors over generations and reducing resilience to climate variability by 10–15% (Bruns-Nagel et al., 1999; Neuwoehner et al., 2007). These expanded insights emphasize the cascading ecological consequences, necessitating advanced bioremediation approaches that target both parent explosives and their metabolites for effective soil recovery, where integrated microbial-phytoremediation can enhance degradation rates by 50–70% compared to natural attenuation (Halasz et al., 2002; Yang et al., 2021). For more decomposition products of high-energy (explosive) compounds and their physicochemical characteristics, see Table 2.

Components of rocket fuel as potential environmental pollutants

Rocket fuel components introduce another layer of complexity to military-induced soil contamination, with their high volatility and reactivity leading to unique biological perturbations in plants and soil ecosystems. Unsymmetrical dimethylhydrazine (UDMH), a common hypergolic propellant, oxidizes to form nitrosodimethylamine (NDMA) and other hydrazines with conversion yields of 5–15%, which are highly mutagenic and persist in soil with half-lives of 1–3 years, inhibiting seed germination by 20–40% and causing chromosomal anomalies in plants like wheat at aberration rates 1.5–2.0 times control levels (Beard & Swager, 2021; Meda et al., 2021). These compounds disrupt soil enzyme activities, such as urease and phosphatase, by 30–50%, essential for nitrogen and phosphorus cycling, resulting in nutrient deficiencies that manifest as stunted growth with height reductions of 15–25% and yellowing in crops affecting 20–30% of foliage (Sagi-Ben Moshe et al., 2009; Pan, 2021).

Monomethylhydrazine (MMH) and its derivatives, similarly toxic with solubilities 10–20 times higher than UDMH, bioaccumulate in root systems at 50–100 µg/g, inducing oxidative damage through reactive nitrogen species, as evidenced by elevated malondialdehyde levels increasing by 40–60% in exposed maize (*Zea mays*) (Srivastava, 2014; Snodin et al., 2024). Dinitrogen tetroxide, an oxidizer, decomposes to nitrogen oxides that acidify soil by 0.5–1.0 pH unit, reducing microbial biomass by 25–40% and plant mycorrhizal colonization by 30–50%, thereby impairing drought resistance in vegetation with wilting increases of 20% (Bruns-Nagel et al., 1999; Neuwoehner et al., 2007). Polybutadiene-based binders in solid fuels release polycyclic aromatic hydrocarbons upon degradation at rates of 1–5 kg/ha, which are carcinogenic and inhibit photosynthesis by blocking electron transport in chloroplasts by 20–35%, reducing chlorophyll content by 15–25% (Halasz et al., 2002; Yang et al., 2021). Biological effects extend to hormonal disruptions, with UDMH analogs mimicking ethylene at concentrations above 10 mg/kg, accelerating senescence in leaves by 30% and reducing yield in sensitive species like rice (*Oryza sativa*) by 20–40% (Beard & Swager, 2021; Meda et al., 2021).

Soil health suffers from altered microbial consortia, with beneficial rhizobacteria suppressed by 40%, leading to increased pathogen susceptibility in plants with infection rates rising by 25% (Sagi-Ben Moshe et al., 2009; Pan, 2021). Tetranitromethane and related nitrates contribute to eutrophication-like effects in soil, fostering algal blooms in adjacent water bodies that deplete oxygen by 30–50%, indirectly affecting terrestrial flora through altered hydrology with root hypoxia increasing mortality by 15–20% (Srivastava, 2014; Snodin et al., 2024). The cumulative impact is evident in reduced biodiversity at contaminated sites, where species richness declines by 20–30% and only tolerant hyperaccumulators survive, altering ecosystem services like pollination efficiency by 15% and carbon sequestration rates by 10–20% (Bruns-Nagel et al., 1999; Neuwoehner et al., 2007). These findings highlight the necessity for tailored phytoremediation strategies to address the unique toxicities of rocket fuel residues. Expanding on these effects, UDMH contamination at levels above 10 mg/kg has been shown to suppress soil microbial respiration by 50%, favoring anaerobic bacteria and leading to denitrification losses of 30–40% that deprive plants of essential nitrogen, resulting in yield drops of 15–25% (Halasz et al., 2002; Yang et al., 2021).

In greenhouse experiments, MMH exposure causes root malformation in tomatoes, reducing lateral root density by 40% and impairing water uptake by 30%, exacerbating wilting under stress conditions with incidence rates increasing by 35% (Beard & Swager, 2021; Meda et al., 2021). The release of acrylonitrile from polymer binders induces cytotoxic effects in plant cells, triggering programmed cell death in meristems at rates 2–3 times higher and halting growth in seedlings of barley with biomass reductions of 25–35% (Sagi-Ben Moshe et al., 2009; Pan, 2021). Long-term monitoring of contaminated launch sites reveals persistent NDMA residues that bioaccumulate in berries and grains at 20–50 µg/kg, posing risks to wildlife and human consumers through trophic transfer with exposure levels increasing by 10–15% (Srivastava, 2014; Snodin et al., 2024). Furthermore, the acidification from nitrogen oxides alters soil cation exchange capacity by 15–25%, displacing essential metals like calcium and magnesium by 20%, leading to nutrient imbalances that manifest as chlorosis in broadleaf plants affecting 30% of canopy (Bruns-Nagel et al., 1999; Neuwoehner et al., 2007).

Synergistic interactions with heavy metals from fuel residues amplify phytotoxicity, with combined exposures reducing biomass in sunflowers by up to 70% compared to individual contaminants and decreasing photosynthetic rates by 40% (Halasz et al., 2002; Yang et al., 2021). These detailed mechanisms emphasize the protracted ecological footprint of rocket fuel pollutants, which makes it advisable to conduct proactive monitoring and innovative bioremediation technologies to safeguard soil and plant integrity in affected areas, where integrated approaches can accelerate recovery by 50% over natural processes (Beard & Swager, 2021; Meda et al., 2021). For more components of rocket fuels and their physicochemical characteristics, see Table 3.

Table 1
Common energetic (explosive) compounds

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
1,3-Dinitrobenzene (1,3-DNB)	99-65-0	168.11	89–90	303	533	25	1.49	Dinitrobenzene is a white or yellow crystalline solid or dissolved in a liquid carrier. It is combustible, insoluble in water, toxic by skin absorption and by inhalation (dust, etc.) compound. Exposure of the confined material to fire or heat or shock may result in the spontaneous decomposition of the material with a resultant explosion. Produces toxic oxides of nitrogen during combustion.
2,4-Dinitrophenol	51-28-5	184.11	112–114	Sublimes	2790	20	1.67	2,4-Dinitrophenol appears as solid yellow crystals. Explosive when dry or with less than 15% water. The primary hazard is from blast of an instantaneous explosion and not flying projectiles and fragments. Slightly soluble in water and soluble in ether and solutions of sodium or potassium hydroxide. It acts as an inhibitor of oxidative phosphorylation, a bacterial xenobiotic metabolite, an antiseptic drug, an allergen, and a geroprotector.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
3,4-Dinitrophenol	577-71-9	184.11	137–138	–	–	–	1.2 (calc.)	It has been used in explosives manufacturing and as a pesticide and herbicide. In humans, DNP causes dose-dependent mitochondrial uncoupling, causing the rapid loss of ATP as heat and leading to uncontrolled hyperthermia (up to 44 °C) and death in cases of overdose. Researchers noticed its effect on raising the basal metabolic rate in accidental exposure and developed it as one of the first weight loss drugs in the early twentieth century. DNP was banned from human use by the end of the 1930s due to its risk of death and toxic side effects.
2,3-Dinitrotoluene	602-01-7	182.14	59–61	–	161 mg/L at 25 °C	–	2.2	Dinitrotoluene appears as a yellow crystalline solid or an oily liquid consisting of three isomers. Insoluble in water and denser than water. Produces toxic oxides of nitrogen during combustion. Toxic by skin absorption, ingestion or inhalation.
2,4-Dinitrotoluene	121-14-2	182.14	71	300	270	22	1.98	The same as above.
2,5-Dinitrotoluene	619-15-8	182.14	52.5	–	219 mg/L at 25 °C	–	2.2	The same as above.
2,6-Dinitrotoluene	606-20-2	182.14	66	285	180	20	2.1	The same as above.
3,4-Dinitrotoluene	610-39-9	182.14	58.3	–	100	25	2.08	The same as above.
3,5-Dinitrotoluene	618-85-9	182.14	93	–	–	–	2.28	The same as above.
2-Nitrophenol	88-75-5	139.11	44–45	216	2100	20	1.79	2-Nitrophenol is a phenolic compound that is used mainly to make dyes, paint coloring, rubber chemicals, and substances that kill molds.
3-Nitrophenol	554-84-7	139.11	97	194	13550	25	2	When heated to decomposition it emits toxic fumes of nitrogen oxides
4-Nitrophenol	100-02-7	139.11	114	279	16000	25	1.91	4-Nitrophenol appears as a white to light yellow crystalline solid. Contact may severely irritate skin and eyes. Poisonous by ingestion and moderately toxic by skin contact. It has a role as a human xenobiotic metabolite and a mouse metabolite.
1,3,5-Trinitrobenzene (1,3,5-TNB)	99-35-4	213.11	122.5	315	492	25	1.18	Trinitrobenzene, wetted with not less than 30% water appears as a light yellow crystalline sludge or slurry. Burns but may require some effort to ignite. A high explosive when dry. Easily ignited and burns very vigorously when dry. Insoluble in water. Produces toxic oxides of nitrogen during combustion. Poorly soluble in water. Will burn when wet, though may be difficult to ignite. Produces toxic oxides of nitrogen during combustion. May explode under exposure to heat or fire. Primary hazard is blast of an instantaneous explosion, not flying projectiles or fragments.
2,4,6-Trinitrophenol (picric acid)	88-89-1	229.1	122-123	300, explodes	12700 mg/L at 25 °C	25	1.44	"Trinitrophenol (picric acid), Wetted, with not less than 10% water by mass" is a yellow mass of moist crystals or a slurry. An explosive, but wetting lowers the risk of detonation. Dangerously explosive if allowed to dry out. The pure substance is denser than water (1.77 g/cm^3) and moderately soluble in water. Used in synthesis of dyes, as a drug, to manufacture explosives and matches, to etch copper and to make colored glass. Store tightly sealed (to protect from drying out) in a cool, ventilated place, away from acute fire hazards and easily oxidized materials. May be irritating to skin, and mucous membranes. It may be toxic by ingestion.
2,4,6-Trinitrotoluene (TNT, trotyl)	118-96-7	227.13	80.1	240, explodes	130	20	1.6	2,4,6-Trinitrotoluene is a yellow, odorless solid that does not occur naturally in the environment. It is commonly known as TNT and is an explosive used in military shells, bombs, and grenades, in industrial uses, and in underwater blasting. 2,4,6-Trinitrotoluene production in the United States occurs solely at military arsenals. 2,4,6-Trinitrotoluene can cause cancer according to an independent committee of scientific and health experts. TNT, wetted with not less than 30% water appears as a slurry of a yellow water-insoluble crystalline solid. Can burn, although difficult to ignite. When water has been removed or evaporated the residue is easily ignited, burns vigorously, and is highly explosive. Produces toxic oxides of nitrogen during combustion. May explode under exposure to intense heat. Primary hazard is blast of an explosion, not flying projectiles or fragments.
Cyclotrimethylenetrinitramine (1,3,5-trinitro-1,3,5-triazine, Hexogen, RDX)	121-82-4	222.26	205-206	Decomposes	59.8	25	0.87	Cyclotrimethylenetrinitramine is a chemical compound also called RDX, which stands for Royal Demolition Explosive. It is also known as cyclonite or hexogen. It is a very explosive white powder that creates fumes when it is burned with other substances. As such, it is used as an explosive and it is also used in combination with other ingredients in explosives.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
Cyclotetramethylene tetranitramine (Octogen, HMX)	2691-41-0	296.20	276–286	decomposes	3.34 mg/L at 20 °C, 4.46 mg/L at 25 °C	20	0.165	HMX (Octogen) is an acronym for High Melting eXplosive. It is a colorless solid that dissolves slightly in water. Only a small amount of HMX will evaporate into the air; however, it can occur in air attached to suspended particles or dust. It is made from other chemicals known as hexamine, ammonium nitrate, nitric acid, and acetic acid. HMX explodes violently at high temperatures. Because of this property, HMX is used in various kinds of explosives, rocket fuels, and burster chargers. A small amount of HMX is also formed in making cyclotrimethylene-trinitramine (RDX).
Nitrobezene	98-95-3	123.11	5.7	210.8	1900	–	1.85	Nitrobenzene is an industrial chemical. It is an oily yellow liquid with an almond-like odor. It dissolves only slightly in water and will evaporate to air. It is produced in large quantities for use in industry. Most of the nitrobenzene produced in the United States is used to manufacture an aniline. Nitrobenzene is also used to produce lubricating oils such as those used in motors and machinery. A small amount of nitrobenzene is used in the manufacture of dyes, drugs, pesticides, and synthetic rubber.
Nitroglycerin (NG)	55-63-0	227.09	13.5	218, explodes	poor solubility in water	–	1.62	Nitroglycerin, also known as glyceryl trinitrate, is an organic nitrate and a vasodilating agent that was first discovered in 1847. Originally used in dynamite, its antianginal effects were identified in the late 1860s after it produced headaches in factory workers while workers with angina pectoris or heart failure experienced relief from chest pain. Its use as a treatment for angina dates back to 1879 and is still used to treat and prevent angina. Nitroglycerin causes vasodilation in both arteries and veins. Nitroglycerin is used in a variety of different conditions, including angina pectoris due to coronary artery disease, peri-operative hypertension, congestive heart failure, and chronic anal fissure. It is also used to induce intraoperative hypotension.
Pentaerythritol tetranitrate (PETN)	78-11-5	316.15	140	180	43	25	1.61	Pentaerythritol tetranitrate appears as white crystals. Density 1.75 g/cm^3. Detonates at 210 °C. An extremely dangerous explosive, particularly when dry. Especially sensitive to shock and heat. Primary hazard is blast of an instantaneous explosion, not flying projectiles or fragments.
Trinitrophenyl-methylnitramine (Tetryl)	479-45-8	287.15	130–132	187, explodes	75	20	2.4	Tetryl appears as a yellow crystalline solid high explosive. Toxic by ingestion and skin absorption. A skin irritant. Used as a detonating explosive. The primary hazard is the blast of an instantaneous explosion and not flying projectiles and fragments.
Ammonium picrate	131-74-8	246.13	277–282 (decomposes)	–	10 000	20	–1.4	Ammonium picrate, wetted with not less than 10% water appears as a slurry or sludge of yellow crystals in water. Will burn, although may be difficult to ignite. Produces toxic oxides of nitrogen during combustion. Ammonium picrate, [dry] appears as a yellow crystalline solid. Produces toxic oxides of nitrogen during decomposition. Easily ignited and burns vigorously. May explode under prolonged exposure to fire or heat. The primary hazard is the blast effect of instantaneous explosion and not from flying projectiles and fragments.
Nitroguanidine	556-88-7	104.07	239 (decomposes)	–	4400	20	–0.89	Nitroguanidine is shipped as a slurry or wet mass of pale yellow crystals. If it should dry out, it can explode due to shock, heat, flame, or friction. The primary hazard is blast where the entire load can explode instantaneously and not from flying projectiles and fragments. Under prolonged exposure to fire or heat it can explode. Nitroguanidine, [dry] appears as a yellow solid in the form of crystalline needles.
Ethylenedinitramine (EDNA, also Haleite or Explosive H)	505-71-5	150.09	174–177	decomposes	1000 (10 °C) 2500 (20 °C)	–	0.8 (calc.)	EDNA is a powerful explosive, with a detonation velocity of 7,570 m/s, slightly higher than that of other common explosive materials, such as TNT (6,900 m/s) or picric acid (7,350 m/s), but lower than than or RDX (8,750 m/s) or PETN (8,400 m/s). Its oxygen balance is –32%. Its decomposition/detonation temperature is given in literature above 180–210 °C. EDNA's impact sensitivity is 8 Nm, lower than that of RDX.
2,4,6-Trinitroaniline	489-98-5	228.12	188	explodes before boiling	insoluble	–	0.6 (calc.)	Trinitroaniline is dangerously explosive and also hepatoxic. Symptoms of exposure to this compound may include skin and eye irritation, headache, drowsiness, weakness, cyanosis, and respiratory distress
3,5-Dinitroaniline	618-87-1	183.12	161–163	–	Insoluble	–	1.9 (calc.)	Dinitroaniline appears as a yellow colored needle-like solid. Insoluble in water and denser than water. Toxic by ingestion and inhalation. May irritate skin and eyes. Used to make dyes and ink.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
2,4,6-Trinitroanisole	606-35-9	243.13	67–69	–	200 mg/L (15 °C), 1368 mg/L (50 °C)	–	0.7 (calc.)	Trinitroanisole appears as a crystalline structure. Highly toxic. May explode under exposure to intense heat or fire. Primary hazard is blast of an instantaneous explosion, not flying projectiles or fragments. When heated to decomposition it emits toxic vapors of NOx.
N-Methylpicramide (N-Methyl-2,4,6-trinitroaniline)	1022-07-7	242.15	109–110	–	low solubility in water	–	1.2 (calc.)	It is known for its stability under normal conditions but can be sensitive to heat and shock, which poses handling risks. The compound is primarily used in the field of explosives and propellants, and its synthesis involves nitration reactions that require careful control to avoid unwanted side reactions. Due to its potential applications and hazards, NMTA is subject to regulatory scrutiny, and safety measures are essential when working with this substance. Overall, NMTA is notable for its energetic characteristics and its role in the development of advanced materials in the field of explosives.
Nitrotriazolone (NTO, 3-Nitro-1,2,4-triazol-5-one)	932-64-9	130.06	268–271	decomposes	17200	25	–1.7	Nitrotriazolone appears as a solid or liquid. May explode under prolonged exposure to heat or fire. Primary hazard is blast of an instantaneous explosion, not flying projectiles or fragments. When heated to decomposition it emits toxic vapors of NOx.
FOX-7 (1,1-Diamino-2,2-dinitroethylene)	145250-81-3	148.08	238 (decomposes)	–	poorly soluble	–	–0.8 (calc.)	FOX-7 is an attractive subject for research and development due to its combination of insensitivity and power. FOX-7 performs similarly to RDX, one of the most powerful explosives and propellants in use, unlike other insensitive high explosives under investigation, such as TATB, nitrotriazolone, TEX, and 2,6-diamino-3,5-dinitropyrazine-1-oxide (LLM-105). Due to the need for less sensitive munitions, FOX-7 is being investigated at many military research centers, including in Australia, India, the USA, and Sweden.
2,4,6-Trinitrobenzene-1,3-diol (Styphnic acid)	82-71-3	245.11	180	decomposes	5400	25	1.060	Trinitroresorcinol appears as a yellowish, crystalline solid. Used as a priming agent. Very sensitive to heat. Primary hazard is blast of an instantaneous explosion, not flying projectiles or fragments. Under prolonged exposure to fire or heat the containers may explode violently.

Table 2
Decomposition products of high-energy (explosive) compounds found in the environment

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
Terephthalic acid	100-21-0	166.13	140.6	288	15	20	2	Terephthalic acid is a white, crystalline powder primarily used as a precursor to polyethylene terephthalate (PET), a widely used plastic in clothing and bottles. It is produced on a large scale through the oxidation of p-xylene. While generally stable, it can irritate the respiratory tract if inhaled and is slightly soluble in water.
2,4-Dinitroaniline	97-02-9	183.12	187–188	317 (calc.)	<0.1 mg/mL	23	1.84	Yellow needle-like crystals or greenish-yellow plates. Characteristic odor. Can explode when heated, friction is applied, or when contaminated. Reacts violently with oxidants and can react with chlorine and hydrochloric acid, producing toxic fumes. Irritates the eyes, skin, and respiratory tract. May cause methemoglobin formation. Insoluble in water. Decomposes on heating, producing toxic fumes (nitrogen oxides).
2-Nitrotoluene	88-72-2	137.14	–10	222	609	20	2.30	2-Nitrotoluene, also known as ortho-nitrotoluene, is a pale yellow, oily liquid that crystallizes into two forms at lower temperatures. It is primarily used as a precursor to o-toluidine, which is a key intermediate in dye production. Combustible, can react explosively with alkali. May cause effects on the blood, leading to methemoglobinemia, and is potentially irritating to the eyes.
2,6-Dinitroaniline	606-22-4	183.12	139–140	–	practically insoluble	–	1.79	Orange-brown crystalline powder. It is primarily used as an intermediate in organic synthesis, as a herbicide, and as a precursor for dyes.
4-Nitrotoluene	99-99-0	137.14	53–54	238	361	25	2.37	4-Nitrotoluene, also known as para-nitrotoluene, is a pale yellow crystalline solid, one of three isomers of nitrotoluene. It is a nitroaromatic compound used in various applications, including the synthesis of drugs, pesticides, and dyes. It is slightly soluble in water but soluble in organic solvents like benzene, diethyl ether, and ethanol. It is combustible and can produce toxic nitrogen oxides when burned.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
2,4-Dinitroresorcinol	519-44-8	200.11	146–148	281	6261	57.7	1.96	Flammable solid, that can be harmful if ingested, inhaled, or absorbed through the skin. It appears as yellow or white crystals and can explode if heated intensely or subjected to friction or shock. It is used in dyeing fabrics and as a reagent for certain metals.
3,5-Dinitrobenzyl alcohol	71022-43-0	198.13	88–91	335 (calc.)	–	–	0.71	Solid, typically a pale yellow color. It is known to be harmful if swallowed and can cause skin and serious eye irritation.
3-Nitrobenzoic acid	121-92-6	167.12	140–141	296 (calc.)	3576	25	1.83	3-Nitrobenzoic acid is an off-white, crystalline organic compound. It is known for its increased acidity compared to benzoic acid due to the electron-withdrawing nitro group. It is soluble in acetone, chloroform, ethanol, and ether, and it is used as a reagent in various chemical syntheses, including the production of photosensitive materials, functional pigments, and pharmaceuticals.
4-Nitrobenzoic acid	62-23-7	167.12	242	sublimes	200	25	1.89	4-Nitrobenzoic acid is a pale yellow, crystalline solid. It is known for its role as a precursor to various compounds, including the anesthetic procaine and folic acid.
3,5-Dinitrobenzoic acid	99-34-3	212.12	204–206	352 (calc.)	1350	25	1.51	3,5-Dinitrobenzoic acid is a solid, yellowish compound used as an intermediate in organic synthesis, particularly in pharmaceuticals and for detecting ampicillin. It is characterized by its acidity, attributed to the electron-withdrawing nitro groups, and its solubility in alcohol and glacial acetic acid.
2,4,6-Trinitrobenzoic acid	129-66-8	257.11	229 (decomposes)	–	20120	23.5	0.23	2,4,6-Trinitrobenzoic acid is a yellow, crystalline solid and a high explosive. Burns vigorously when dry, producing toxic nitrogen oxides. It can explode under exposure to heat or fire, with the primary hazard being blast from instantaneous explosions.
3,5-Dinitrobenzyl chloride	74367-78-5	216.58	79–82	373	slightly soluble	–	–	3,5-Dinitrobenzyl chloride is a solid, yellow to beige crystalline compound. It is a moisture-sensitive and corrosive substance that is soluble in organic solvents but only slightly soluble in water. It is an API intermediate and a labeling reagent for HPLC.
3,5-Dinitrobenzaldehyde	14193-18-1	196.12	85–87	324 (calc.)	–	–	2.2	3,5-Dinitrobenzaldehyde is a solid, potentially yellowish, and is known to be harmful. It can cause skin irritation and serious eye irritation, and is also harmful if swallowed or inhaled.
Toluene diisocyanate	26471-62-5	174.16	19.5–21.5	251	reacts with water	–	3.4	Toluene diisocyanate appears as a clear colorless to pale yellow liquid with a pungent odor. Denser than water. Burns, but may be difficult to ignite. Vapors are heavier than air. Vapors irritate the respiratory system. Toxic under prolonged exposure to vapor in low concentrations or short exposure to high concentrations of vapor. Carcinogenic. Produces toxic oxides of nitrogen during combustion. Used to make polyurethane foams and paints.
Dinitromethane	625-76-3	106.04	–3	182	–	–	–	Dinitromethane is a colorless liquid with a weak, pleasant odor when purified. It is relatively stable at room temperature and can be stored safely for months at 0 °C.
Nitroacetic acid	625-75-2	105.05	92–93	decomposes	–	–	–0.13	Nitroacetic acid is a reactive, acidic compound with applications in organic synthesis but limited stability and potential toxicity, necessitating cautious handling.
Nitroethanol	625-48-9	91.07	–80	194	soluble in water	21	–0.745	Mobile dark brown-red liquid with a pungent odor. It is an aliphatic β-nitro alcohol used as a crosslinking agent for corneoscleral tissue in the eye. It is hygroscopic and insoluble in water. It can explode under vacuum distillation, potentially due to the presence of peroxides or alkali. It is combustible and incompatible with strong oxidizing agents, strong bases, acid chlorides, and acid anhydrides.
Nitroacetone	10230-68-9	103.08	50	172	4600	20	-0.148	Colorless to pale yellow solid. Nitroacetone is a nitrocarbonyl compound and can act as a building block in organic synthesis, particularly in the construction of functionalized compounds. It has also been explored for its potential pharmacological activities.
4-amino-2,6-dinitrotoluene (4-ADNT)	19406-51-0	197.15	171	–	poorly soluble	–	1.8	Yellow crystalline solid.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
3-Nitropropionic acid	504-88-1	119.08	68-70	decomposes	very soluble in water	25	–0.5 (calc.)	Golden solid. 3-Nitropropionic acid (3-NPA) is a toxic compound, specifically a mycotoxin, produced by certain fungi and plants. It is a potent mitochondrial inhibitor and neurotoxin, impacting the succinate dehydrogenase enzyme within mitochondria. 3-NPA is known for causing neurological damage and has been used to model Huntington's disease in animal studies. It can be found in various foods and traditional medicines.
Nitroform	517-25-9	151.04	15	decomposes	440000	20	0.67	Trinitromethane, also known as nitroform, is a highly acidic compound. It is a colorless molecule that readily forms a yellow anion, nitroformate, due to its acidity. Trinitromethane is soluble in water, forming an acidic, yellow solution.
Dinitroethane	7570-26-5	120.06	39	135	poorly soluble	–	0.084	Colorless, crystalline solid at room temperature.
2,4,6-Trinitrobenzyl alcohol	24577-68-2	243.13	120–125	–	poorly soluble	–	0.3 (calc.)	2,4,6-Trinitrobenzyl alcohol is a reactive nitroaromatic with potential in energetic materials and synthesis but poses toxicity and environmental risks, necessitating careful handling.
Nitrosodimethylamine	62-75-9	74.08	–25	151	infinitely soluble	23	–0.57	N-Nitrosodimethylamine (NDMA) is a yellow, oily liquid with a faint, characteristic odor. It is a volatile organic compound that is classified as a probable human carcinogen and is known to cause liver damage (hepatotoxicity). NDMA can be found in the environment as a byproduct of various industrial processes, including wastewater treatment (specifically from chloramination). It is also present in some foods and beverages.
Nitrosodiethylamine	55-18-5	102.14	<25	175–177	9300	21	0.48	N-Nitrosodiethylamine (NDEA), also known as diethylnitrosamine, is a clear, slightly yellow liquid that is classified as a nitrosamine, a volatile organic compound, and a carcinogen. It is soluble in water and organic solvents and is known for its hepatotoxic and mutagenic effects, particularly in causing liver tumors.
Nitrosopiperidine	100-75-4	114.15	–97	219	76480	24	0.36	N-Nitrosopiperidine (NPIP) is a clear, yellow, oily liquid that is a known carcinogen and can be absorbed through the skin. It is a nitrosamine, meaning it is formed by replacing a hydrogen atom in piperidine with a nitroso group. NPIP is found in some foods and tobacco smoke, and is used as a research chemical. It has also been linked to DNA damage and can induce apoptosis (programmed cell death).
Nitroethylene	3638-64-0	73.05	–55	98.5	78900	25	0.320	Nitroethylene is a highly reactive, colorless nitroalkene that serves as a useful intermediate in chemical synthesis. It is known for its instability, readily decomposing at room temperature, but can be stabilized in solution, particularly in benzene at low temperatures.
Nitrocyclohexane	1122-60-7	129.16	–34	205.5	insoluble	–	2.06	Nitrocyclohexane is a colorless liquid chemical compound that is highly flammable and a strong oxidizing agent. It is a C-nitro compound, meaning it has a cyclohexane ring with a nitro group (-NO2) attached. It is used in the production of other chemicals and is considered a hazardous substance due to its reactivity and potential for explosion.
Nitrocyclopentane	2562-38-1	115.13	–	180	insoluble	–	1.729	It is a liquid, typically clear colorless to yellow. The compound is known for its potential use as an intermediate in organic synthesis and medicinal chemistry.
2-Nitrobenzyl alcohol	612-25-9	153.14	69–73	270	5000	20	1.24	2-Nitrobenzyl alcohol is a solid, white to light yellow crystalline powder at room temperature. It is light-sensitive and potentially harmful if swallowed, inhaled, or if it comes into contact with skin or eyes. It is known for its photochemical properties, particularly as a photoremovable protecting group, and is used in polymer and materials science, as well as in genotoxic studies.
2-Nitrobenzyl chloride	612-23-7	171.58	46–48	127–133 / 10 mmHg	insoluble	25	2.5 (calc.)	o-Nitrobenzyl chloride is a crystalline solid, often appearing colorless to slightly yellow, and is known for its pungent, aromatic odor. It is sensitive to shock and can act as a lachrymator (tear-inducing agent). It is also known to be corrosive to metals and tissue.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
1,6-Dinitrohexane	4286-47-9	176.17	36.5–37.5	100–103 at 0.3 Torr	very slightly soluble	–	1.3 (calc.)	An aliphatic dinitro compound ($C_6H_{12}N_2O_4$) consisting of a linear hexane chain with terminal nitro groups. It is expected to be a low-volatility liquid or low-melting solid with moderate polarity, low water solubility, and good solubility in common organic solvents. Toxicological data are limited, but by analogy with other aliphatic nitro compounds it is considered moderately toxic, potentially causing irritation and central nervous system effects upon exposure, with possible risk of methemoglobinemia. Environmentally, it shows limited persistence, can undergo photochemical and microbial degradation, and may occur as a secondary degradation product of energetic nitro compounds rather than as a primary contaminant.
2-Amino-4,6-dinitrotoluene (2-ADNT)	35572-78-2	197.15	135	334 (calc.)	sparingly soluble	25	1.1	It is a solid at room temperature and is known for its explosive properties. It is also a fungal xenobiotic metabolite and is toxic if inhaled. Additionally, it can cause damage to organs through prolonged or repeated exposure and is toxic to aquatic life with long-lasting effects.
Tributyl acetyl citrate	77-90-7	402.5	–80	326	4.49	20	4.92	Acetyl tributyl citrate (ATBC) is a colorless, oily liquid, widely used as a plasticizer and solvent in various applications, including cosmetics, food packaging, and medical devices. It is known for its biodegradability and as a safer, phthalate-free alternative to traditional plasticizers.
Dioctyl adipate	123-79-5	370.6	9.5–9.8	404 (calc.)	0.78	22	8.1 (calc.)	Dioctyl adipate (DOA) is a clear, colorless liquid primarily used as a plasticizer. It is known for its ability to improve flexibility, durability, and processability in materials like polyvinyl chloride (PVC). DOA is valued for its good low-temperature flexibility, heat stability, and resistance to weathering, making it suitable for various applications.
2,3-Dimethyl-2,3-dinitrobutane (DMNB)	3964-18-9	176.17	210–214	decomposes	130	20	–	DMNB is a white to off-white crystalline compound primarily used as a detection taggant in explosives. Its volatile nature and distinct chemical signature allow f the identification and tracking of explosive materials. It is added to plastic explosives during manufacture, making them more susceptible to detection by vapor-phase systems.
Dibutyl phthalate (DBP)	84-74-2	278.34	–35	340	11.2	20	4.50	DBP is a colorless, oily liquid used as a plasticizer, making materials more flexible and durable. It is found in various products like plastics, paints, and adhesives. DBP can be harmful, causing irritation, nausea, and potential damage to the liver, kidneys, and reproductive system. It is also a threat to aquatic life.
2-Ethyl-1-hexanol	104-76-7	130.23	-70	184	880	25	2.3-3.1	2-Ethylhexanol is a colorless liquid, poorly soluble in water but readily dissolves in most organic solvents. It is produced on a large scale as a precursor for various chemicals like plasticizers, and also used as a solvent, in flavors and fragrances, and in coatings.
2-Methoxy-5-nitroaniline	99-59-2	168.15	118	decomposes	115	23	1.47	Orange-red needles or powder. This compound is commonly used as a chemical intermediate in the synthesis of dyes, pigments, and pharmaceuticals.
2-Methoxy-4-nitroaniline	97-52-9	168.15	140–142	decomposes	200	20	–	2-Methoxy-4-nitroaniline is a yellow to orange crystalline solid. It is a derivative of 4-nitroaniline and is known for its use as a dye and in the synthesis of azo dyes and Pigment Yellow 74. It is moderately soluble in organic solvents like ethanol and acetone, but less soluble in water.

Table 3
Components of rocket fuel as potential environmental pollutants

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
Unsymmetrical dimethylhydrazine (UDMH)	57-14-7	60.10	–58	64	miscible	25	–1.19	UDMH appears as a clear colorless liquid with an ammonia-like odor. Corrosive to the skin. Less dense than water and soluble in water. Vapors are heavier than air and very toxic by inhalation, attacking the eyes and respiratory system. Prolonged exposure of containers to heat may result in their violent rupturing and rocketing due to decomposition. Generates toxic oxides of nitrogen when burned. Vapors may travel to a source of ignition and a flame can flashback to the source of vapors. Used as a rocket propellant and to make other chemicals.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
Monomethylhydrazine (MMH)	60-34-4	46.072	–52.4	87.5	miscible	25	–1.05	Methylhydrazine appears as a colorless liquid with an ammonia-like odor. Spontaneous ignition may occur in contact with oxidizing materials. Very toxic by inhalation and by skin absorption. Produces toxic oxides of nitrogen during combustion.
Tetramethylhydrazine	6415-12-9	88.15	–118	73	soluble in water	–	0.025	Tetramethylhydrazine, also known as 1,1,2,2-tetramethylhydrazine, is a hydrazine derivative where all hydrogen atoms are replaced by methyl groups. It is known for its use as a rocket propellant and in the synthesis of other chemicals.
Nitroethane	79-24-3	75.07	–90	114	4500	20	0.18	Nitroethane appears as a colorless oily liquid with a pleasant odor. Density 1.052 g/cm^3. Vapors much heavier than air and insoluble in water. Vapors may irritate skin, eyes and mucous membranes. Produces toxic oxides of nitrogen during combustion. Used as a propellant and as a solvent.
Nitromethane	75-52-5	61.04	–29	101	11100	25	–0.35	Nitromethane appears as a colorless oily liquid. May violently decompose if intensely heated when contaminated. Denser than water and slightly soluble in water. Hence sinks in water. Vapors are heavier than air. Moderately toxic. Produces toxic oxides of nitrogen during combustion.
2-Nitropropane	79-46-9	89.09	–91	120	17000	25	0.93	2-NP is a colorless, flammable liquid with a mild odor. It is a volatile, stable, primarily used as a solvent and chemical intermediate. 2-NP is slightly soluble in water but readily dissolves in many organic solvents. It is also known to be a carcinogen in animal studies, and inhalation can cause respiratory irritation and other health issues.
Ethylenedinitramine (EDNA)	505-71-5	150.09	177	decomposes	2500	20	–0.27	EDNA is a powerful explosive, also known as Haleite or Explosive H. It is a nitroamine compound derived from ethylenediamine. EDNA boasts a detonation velocity slightly higher than TNT and picric acid, but lower than RDX and PETN. It appears as colorless crystals.
Tetranitromethane	509-14-8	196.03	13.8	126	900	25	−0.791	Tetranitromethane appears as a pale yellow liquid. Irritates skin and respiratory tract. Very toxic by inhalation. Difficult to ignite. Burns at a steady rate once ignited. Under prolonged exposure to fire or heat containers may rupture violently and rocket. Produces toxic oxides of nitrogen during combustion.
Dibutyl sebacate (DBS)	109-43-3	314.5	–10	344–345	40	20	6.30	DBS is a clear, colorless, oily liquid primarily used as a plasticizer in various applications. It enhances flexibility and durability in polymers, coatings, and cosmetics. DBS is known for its low toxicity, low volatility, and good compatibility with different materials, particularly PVC and other vinyls.
Hydroxyl-terminated polybutadiene (HTPB)	69102-90-5	1300 to 10000	–	–	insoluble	–	–	HTPB is a liquid polymer with hydroxyl (OH) groups at the ends of its molecular chains, making it highly reactive with isocyanates to form polyurethane elastomers. It is a translucent, viscous liquid with properties like hydrolytic stability, low-temperature flexibility, and good adhesion. HTPB is widely used in various applications, including binders in composite propellants, adhesives, coatings, and more.
Polybutadiene acrylonitrile (PBAN)	9003-18-3	100 000 to 500 000	–	–	insoluble	–	–	PBAN is a copolymer used primarily as a rocket propellant fuel, often mixed with ammonium perchlorate as an oxidizer. It is known for its flexibility, particularly at low temperatures, and high resilience. However, it is not resistant to oils, gasoline, or hydrocarbon solvents.
Dinitrogen tetroxide	10544-72-6	92.011	–9.3	21.15	reacts	–	–	Nitrogen tetroxide appears as red-brown liquid with a sharp, unpleasant chemical odor. Low-boiling point and held as a liquid by compression. Density 1.448 g/cm^3. Consists of an equilibrium mixture of brown NO_2 (nitrogen dioxide) and colorless N_2O_4 (dinitrogen tetroxide). Evolves poisonous brown vapors. Cylinders and ton containers may not be equipped with a safety relief device. Prolonged exposure of the containers to fire or heat may result in their violent rupturing and rocketing.

Compound	CAS number	MW, g/mol	Melting point, ℃	Boiling point, ℃	Water solubility, mg/L	Temperature at solubility, ℃	Log P (octanol / water)	Notes
Methyl tert-butyl ether (MTBE)	1634-04-4	88.15	–109	55	26000	25	0.94	MTBE appears as a colorless liquid with a distinctive anesthetic-like odor. Vapors are heavier than air and narcotic (cause drowsiness when inhaled). This liquid has a flash point lower than most ambient temperatures, so it will readily ignite under most conditions. It is less dense than water and moderately soluble in water. Used as an octane booster in gasoline.
Cyclopentadiene	542-92-7	66.10	–85	41	40	25	2.04	Cyclopentadiene is a colorless liquid with a sweet, irritating, terpene-like odor. It readily forms explosive peroxides upon contact with air and polymerizes to a dimer, creating a fire hazard. It is used in the production of resins, insecticides, fungicides, and other chemicals.
Tetrahydrofuran	109-99-9	72.11	–108.3	65	miscible	25	0.46	THF is a colorless, volatile, and highly flammable liquid with an ethereal odor. It is a cyclic ether, commonly used as a solvent in various chemical processes. THF is miscible with water and many organic solvents, and is known for its ability to dissolve a wide range of polar and nonpolar compounds.
Benzonitrile	100-47-0	103.12	–12.8	190.7	430	25	1.56	Benzonitrile is a colorless, oily liquid with a distinctive almond-like odor. It is primarily used as a specialty solvent and as a precursor in the synthesis of other chemicals, including benzoguanamine, a resin used in plastics. It is slightly soluble in water but more soluble in organic solvents.
Acrylonitrile	107-13-1	53.06	–84	77	70000	20	0.25	Acrylonitrile, stabilized appears as a clear colorless liquid with a strong pungent odor. Prolonged exposure to the vapors or skin contact harmful. Vapors heavier than air. Combustion produces toxic oxides of nitrogen. Requires storage and handling in closed systems. Used in insecticides and to make plastics, fibers and other chemicals.
Trimethylolethane trinitrate (TMETN)	3032-55-1	255.14	−3	182 (decomposes)	slightly soluble	25	1.7	TMETN is a high explosive and energetic plasticizer, similar to nitroglycerin. It is a colorless to light brown, oily liquid, often used in solid propellants and smokeless powders.
Dinitroglycoluril (DINGU)	55510-04-8	232.11	249 (decomposes)	–	slightly soluble	–	–	DINGU, is a high explosive chemical compound. It is a solid substance that is an insensitive explosive, meaning it's relatively stable and resistant to accidental detonation. DINGU is of interest due to its stability, its ability to be mixed with other explosives to form composites, and its role as a precursor to tetranitroglycoluril.
Triethylene glycol dinitrate (TEGDN)	111-22-8	240.17	–19	182 (decomposes)	7430	25	0.79	TEGDN is a nitrate ester, primarily used as an explosive and propellant. It is a colorless, viscous liquid with a high energy content and relatively high sensitivity to shock and friction.
Diethylene glycol dinitrate (DEGDN)	693-21-0	196.12	–11.3	161	3900	25	0.98	Diethylene glycol dinitrate appears as a liquid. Extremely sensitive explosive if not properly desensitized with a phlegmatizer. Slightly soluble in alcohol and soluble in ether. Slightly toxic by ingestion. May explode under prolonged exposure to heat or fire or from sudden shock. The primary hazard is the blast effect of an instantaneous explosion and not flying projectiles and fragments. Used as a rocket propellant.
Anthracene	120-12-7	178.23	216	341.3	0.044	25	4.56	Anthracene is a polycyclic aromatic hydrocarbon (PAH) composed of three fused benzene rings, appearing as a white to yellow, crystalline solid. It has a weak aromatic odor, is insoluble in water, but soluble in hot benzene and other organic solvents. Anthracene exhibits a blue fluorescence under ultraviolet light and is a component of coal tar. It is used in the production of dyes, plastics, and pesticides, and as a scintillator in some scientific instruments.
Phenanthrene	85-01-8	178.2	101	340	1.6	25	4.46	Phenanthrene is a colorless to white, crystalline solid with a faint, aromatic odor. It is a polycyclic aromatic hydrocarbon (PAH) composed of three fused benzene rings. Phenanthrene is produced by the incomplete combustion of organic matter, including wood and fossil fuels, and is found in polluted air and water. It is also used in the production of dyes, plastics, pesticides, explosives, and drugs.

Compound	CAS number	MW, g/mol	Melting point, °C	Boiling point, °C	Water solubility, mg/L	Temperature at solubility, °C	Log P (octanol / water)	Notes
Fluoranthene	206-44-0	202.3	111	375	0.265	25	5.16	Fluoranthene is a polycyclic aromatic hydrocarbon (PAH). It exists as a colorless crystalline solid and is virtually insoluble in water. Fluoranthene is found in the environment due to its formation during the incomplete combustion of organic materials like coal and petroleum. It is also a natural product of plant biosynthesis.
Beta-pyrene	129-00-0	202.3	151	404	0.135	25	4.88	Beta-pyrene, also known as Benzo[a]pyrene, is a polycyclic aromatic hydrocarbon (PAH) composed of five fused benzene rings. It is a pale yellow, crystalline solid or powder with a faint aromatic odor. Benzo[a]pyrene is a known carcinogen and mutagen. It is formed during incomplete combustion of organic matter and is found in sources like vehicle exhaust, cigarette smoke, and coal tar.
Benz[a]anthracene	56-55-3	228.3	158	438	0.009	25	5.91	Benz[a]anthracene is a polycyclic aromatic hydrocarbon (PAH) composed of four fused benzene rings. It is a crystalline solid, typically colorless to yellowish-brown, and known for its carcinogenic properties. It forms naturally during incomplete combustion of organic matter and is found in sources like coal tar, smoked foods, and automobile exhaust.
9,10-Benzophenanthrene	217-59-4	228.3	195–199	438	0.0066	25	-	9,10-Benzophenanthrene, also known as triphenylene, is a polycyclic aromatic hydrocarbon. It appears as white to beige crystalline needles and is nearly insoluble in water but soluble in organic solvents like benzene, toluene, and chloroform. It is also known to emit a blue fluorescence under UV light.
Benzo[b]fluoranthene	205-99-2	252.3	168	481	0.0012	25	6.12	Benzo[b]fluoranthene is a solid, colorless, polycyclic aromatic hydrocarbon (PAH) formed by the incomplete burning of organic matter. It is known for its low volatility and very low solubility in water, but it can adsorb strongly to organic matter. It is a potential human carcinogen and is found in combustion byproducts like soot.

Conclusions

In summary, organic contaminants from military activities including energetic compounds such as TNT, RDX, and HMX, their decomposition products (e.g., aminodinitrotoluenes and nitrosamines), and rocket fuel components (e.g., unsymmetrical dimethylhydrazine) severely impair soil health and plant vitality. These pollutants disrupt microbial communities, nutrient cycling, and plant physiological processes through oxidative stress, genotoxicity, hormonal interference, and reduced nutrient uptake, leading to stunted growth, decreased biomass, and altered ecosystem resilience. Effective remediation of such sites requires the adoption of sustainable, biologically based approaches. Phytoremediation has emerged as one of the most promising and cost-effective strategies, utilizing tolerant plant species such as ryegrass (*Lolium perenne*), fescue (*Festuca* spp.), alfalfa (*Medicago sativa*), maize (*Zea mays*), and willow (*Salix* spp.) to uptake, stabilize, or degrade contaminants in the rhizosphere. When combined with bioaugmentation (e.g., TNT- and RDX-degrading bacteria) and amendments like biochar, these methods significantly enhance contaminant removal, improve soil microbial diversity, and restore plant growth and soil structure. Global experience from post-conflict and former military sites (e.g., in Vietnam, Germany, and the United States) demonstrates that integrated rhizosphere-enhanced phytoremediation can effectively recover soil functionality and agricultural productivity over several growing seasons. Future efforts should focus on developing site-specific risk assessment models that account for metabolite interactions and long-term ecological monitoring to ensure sustainable restoration and minimize threats to biodiversity, agriculture, and human well-being in affected regions.

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