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GEOCHEMISTRY OF DEPLETED URANIUM AND URANIUM MILL TAILINGS IN LIBYA

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Abstract: A refined metal by-product of uranium enrichment, depleted uranium (DU) is utilized in ammunition and shielding because of its high density. The sandy waste residue left over from milling ore that contains chemical waste and radioactive decay products is known as uranium mill tailings (UMT) and is kept in dedicated ponds. Geochemistry of depleted uranium and uranium mill tailings is a crucial subject in radioecology and environmental geochemistry in Libya. Assessing environmental pollution, tracking radioactive waste leaks, and evaluating health concerns should be the primary goals of investigating depleted uranium and uranium mill tailings in Libya. Finding soil/groundwater pollution, assessing the long-term effects of radioactive waste, and looking into reported health problems including cancer risks should all be included in the evaluation. The following factors primarily influence how depleted uranium and uranium mill tailings behave in Libya: (1) Arid climate; (2) Reducing conditions; (3) pH; (4) Carbonate concentration; and (5) Mineralogy (phosphate versus sulfate phases).
Keywords: Depleted Uranium, Uranium Mill Tailings, Environmental Geochemistry, Radioecology, Libya.

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1. Introduction

A dense, slightly radioactive byproduct of uranium enrichment, depleted uranium (DU) is mostly composed of U-238 with less U-235. Compared to natural uranium, it is roughly 40-60% less radioactive. It is mostly employed in military armor-piercing ammunition, vehicle armor, and industrial counterweights because of its exceptional density and capacity to pierce armor (e.g., Murray et al., 2002; Monleau et al., 2005; Feugier et al., 2008; Heintze et al., 2011; Harguindeguy et al., 2014; Besic et al., 2017; Lind et al., 2020; Shu et al., 2023; Gürgür et al., 2026). Depleted uranium is categorized as low-level radioactive waste (LLRW), often managed as Class A waste. As a hazardous heavy metal that contaminates soil and water with uranium oxide dust, depleted uranium poses long-term environmental problems, particularly in conflict areas. Particles can linger in the environment, corroding over time, penetrating groundwater, and making their way into the food chain despite their comparatively low radioactivity (Figure 1).

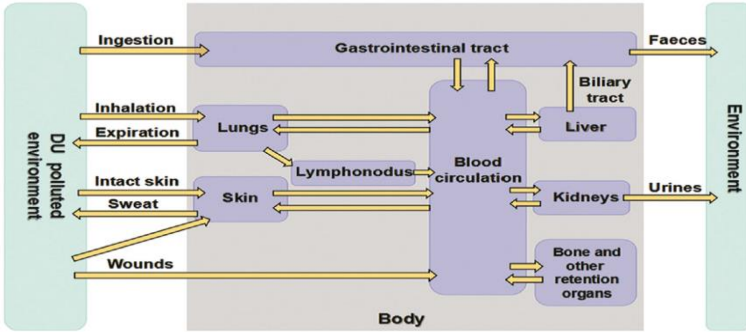

Figure 1. Biokinetic process of depleted uranium contamination

Source: Yue et al. (2018)

Sandy, radioactive byproducts of crushing and chemically processing uranium ore are known as uranium mill tailings (UMT). They contain hazardous heavy metals and around 85% of the radioactivity (Ra-226, Th-230) that was once present in the ore (e.g., Landa, 2004; Mahoney et al., 2007; Nair et al., 2010; Miao et al., 2013; Imteaz et al., 2016; Martínez-Rodríguez et al., 2020; Wang et al., 2022; Hong et al., 2025). In the United States, uranium mill tailings are regarded as a separate category of byproduct material and are not formally categorized as LLRW by regulatory definition. They are handled differently from LLRW Classes A–C, which are usually disposed of in designed surface impoundments, although having a lower activity per unit volume. The long-term environmental hazards linked to uranium mill tailings involve the release of toxic and radioactive substances into the environment. Radon gas emissions, groundwater contamination from seepage, and wind-blown dust distributing radiation into nearby ecosystems are some of the major effects (Figure 2).

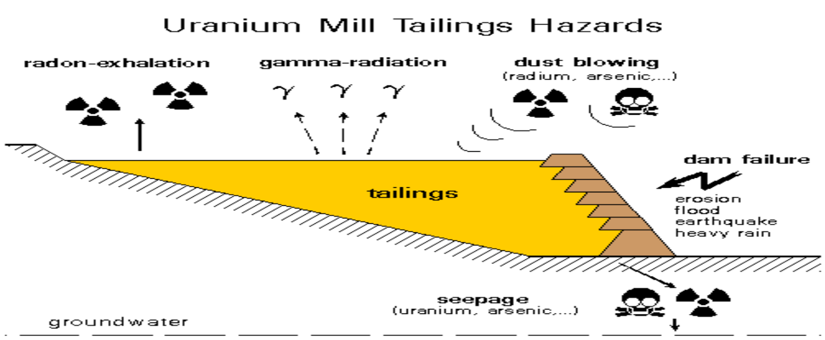

Figure 2. Mechanism of uranium mill tailings toxicity

Source: Diehl (2011)

The chemical behavior, mobility, and environmental effects of uranium when the majority of its fissile isotope (U-235) has been depleted are the main topics of depleted uranium geochemistry. The study of uranium mill tailings geochemistry focuses on the behavior, movement, and transformation of chemical elements in tailings throughout time, particularly in relation to environmental factors like pH, oxygen, and water flow. The distribution of the total lifetime-equivalent dose (TLD) and dilution liability (DL) percentages of humanity's uranium inventory (HUI) by stock type is depicted in Figure (3). The figure illustrates the disproportionate hazard posed by depleted uranium and uranium mill tailings, which together contribute more than 90% of the total risk, despite having received minimal long-term containment planning. This work aims to conduct an investigation of depleted uranium and uranium mill tailings in Libya in order to assess environmental pollution. This uranium waste may have severely polluted the soil and groundwater in Libya, which can result in major health issues.

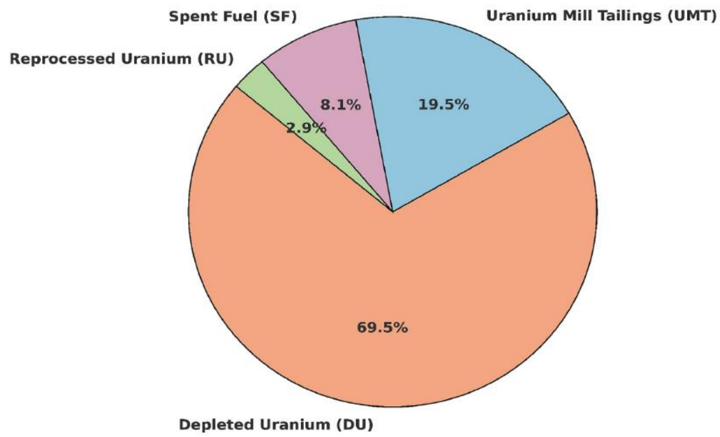

Figure 3. Total lifetime-equivalent dose and dilution liability percentages representing the distribution of humanity's uranium inventory by stock type

Source: Pescatore (2025)

3. Depleted Uranium in Libya

3.1. Sources and Pathways

3.1.1. NATO/U.S.-Led Air Operations in the 2011 Conflict

Although there has been some speculation about potential other channels, the origins of depleted uranium in Libya are mostly associated with military operations, particularly during the 2011 conflict (Elkorghli, 2025).

3.1.2. Contaminated Sites

High radioactivity was found in areas like the 77 Military Base, which was connected to particles frequently linked to DU.

3.1.3. Environmental Spread

Particles have probably been dispersed as a result of locals moving broken military equipment that contained contaminated chemicals without cleaning.

3.1.4. Limited Data

Due to a paucity of information from coalition forces regarding particular types and places of use, it is challenging to monitor the long-term risks associated with these particles.

4. Uranium Mill Tailings in Libya

4.1. Sources and Pathways

4.1.1. Prior to 2003

Prior to 2003, Libya's uranium operations were more concerned with storing yellowcake, or uranium ore concentrate, than with extensive mining or milling wastes. The Tajoura Nuclear Research Center housed a sizable portion of the approximately 1,000 tons of yellowcake that were gathered, most of which came from overseas acquisition. Prior to 2003, there were no significant, publicly recorded conventional mill tailings sites, despite interest in investigating local resources (NTI, 2011).

4.1.2. Missing Material Incident in 2023

Ten barrels with about 2.5 tons of yellowcake went missing from an unmonitored facility in Libya in March 2023, according to the IAEA. Local forces later reportedly found the drums (Plummer, 2023).

4.1.3. Security and Location Challenges

Due to the ongoing unrest in Libya, it has become challenging to secure, monitor, and clean up historic nuclear production, mining, and storage sites.

4.1.4. Environmental Impact

Particularly in the arid, unstable location where materials have been discovered, yellowcake storage places are vulnerable to wind-blown dust dispersal and possible leaching into water supplies. Concerns regarding the long-term management of contaminated sites and the supervision of radioactive materials in Libya are still voiced by the IAEA (Alharathy, 2023).

4.1.5. Limited Data

There is little information available on uranium mill tailings in Libya, which raises concerns about possible radioactive waste that is frequently unreported. The absence of reliable, publicly available monitoring data on radon gas, radioactive dust, and possible soil and groundwater pollution are major worries.

5. Geochemistry of Depleted Uranium and Uranium Mill Tailings in Libya

The general geochemical behavior of depleted uranium, uranium mill tailings, and the unique environmental variables of Libyan soils and groundwater can be combined to understand the geochemistry of these uranium wastes in Libya. Despite the scarcity of field datasets particular to Libya, the procedures are extremely relevant and well-constrained scientifically. Environmental factors greatly influence the mineralogy of uranium; uranyl phosphates usually form stable, immobile phases in alkaline conditions, whereas uranyl sulfates and carbonates are more mobile and soluble, particularly in acidic environments.

Libyan soils are generally classified as semi-arid or arid, and they usually exhibit strongly alkaline conditions (pH 7–9). Due to their low organic matter content and abundance of inorganic carbonates and gypsum, these soils have poor structural stability and water-holding capability. In soil and groundwater, especially at pH>7, carbonate complexation of uranium—mainly in the form of hexavalent U(VI) or uranyl (UO_2^{2+})—significantly improves its solubility, mobility, and environmental movement. In oxic environments, uranyl-carbonate complexes like $UO_2(CO_3)_2^{2-}$ and $UO_2(CO_3)_4^{3-}$ form easily, blocking uranium from adhering to mineral surfaces.

The Libyan deserts are characterized by oxidizing conditions. Under these conditions, uranium transforms into soluble uranyl ions (UO_2^{2+}) and uranium oxides (UO_2, U_3O_8, and UO_3). Solid uranium is dense, but oxidized uranium generates small particles and powders that are mobile, chemically hazardous if swallowed or inhaled, and more likely to spread through the air or water. Moreover, reducing conditions are uncommon but conceivable in Libyan groundwater. Uranium typically occurs in the less soluble U(IV) oxidation state under these conditions, frequently producing persistent solid phases like UO_2 that restrict mobility in groundwater and soil. These conditions, however, may be temporary; if carbonate complexes form or if reducing conditions are not maintained, U(IV) may reoxidize and become mobile.

Isotopic signature is important for tracking depleted uranium in Libya. To identify and track depleted uranium in the environment and differentiate it from natural uranium, the $^{235}U/^{238}U$ ratio is essential. The $^{235}U/^{238}U$ atom ratio of depleted uranium is normally between 0.002 and 0.003. This is far less than the $^{235}U/^{238}U$ atom ratio of natural uranium, which is approximately 0.00725. Furthermore, natural uranium has ratios of $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ that are close to secular equilibrium (≈1), whereas uranium mill tailings show unique isotopic signatures with strong disequilibria, particularly elevated $^{206}Pb/^{207}Pb$ ratios (1.86-7.15) and high $^{34}U/^{238}U$ and $^{230}Th/^{238}U$ activity ratios (1.27-1.87 and 6-65, respectively).

These signals are produced when uranium is separated from its decay products; leaving behind large concentrations of radionuclides like ^{226}Ra. Industrial leaching frequently results in ^{234}U depletion. Table (1) summarizes the environmental impacts of depleted uranium and uranium mill tailings in Libya.

Table 1. Environmental impacts of depleted uranium and uranium mill tailings in Libya

	Depleted uranium	Uranium mill tailings
Soil	Localized contamination hotspots	Widespread contamination if poorly contained
Groundwater	Carbonate-rich ⟶ aquifers increased uranium solubility	(1) Carbonate-rich aquifers ⟶ increased uranium solubility (2) Acid drainage from tailings enhances leaching
Atmosphere	Fine particulate aerosols	Radon gas emission and dust transport

6. Conclusions and Recommendations

In order to evaluate environmental degradation, this effort intended to investigate depleted uranium and uranium mill tailings in Libya. Both natural geological occurrences of uranium-bearing rocks and human activity (mostly the military's usage of depleted uranium) contribute to uranium-related contamination in Libya. Libya does not have a significant uranium mining sector. However, the arid climate, pH, reducing conditions, carbonate concentration, and mineralogy all influence the behavior of uranium in Libya. Uranium and its residues behave significantly in the environment. The following are the most serious risks: (1) Long-term and widespread groundwater contamination; (2) Airborne dust inhalation from depleted uranium and tailings particles; (3) Radon exposure from tailings; and (4) Soil degradation and ecosystem damage.
The key recommendations for mitigating and protecting the environment from the hazards of depleted uranium and uranium mill tailings in Libya are listed below:

i. Monitoring (soil and water sampling, radiological surveys, and air quality monitoring);
ii. Remediation (soil removal (or stabilization), phytoremediation (limited in arid regions), and water treatment systems); and
iii. Tailings management (engineered covers to reduce radon and dust, containment barriers, and long-term site control).

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