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Military-related Heavy Metal Pollution in Soil

A Scientific Review

Abstract

It is well known that during armed conflicts, as well as military trainings, large amounts of pollutants can be released into nature. Of the eleven environmentally toxic elements, Pb, Zn and Cu are often present in high concentrations in the soils of military sites, along with Cd and As. According to newer data from the Russo–Ukrainian War, the inorganic contaminants (mostly toxic elements) show a concentric distribution in the affected areas, caused by artillery activity; however, the spatial distribution of Pb in the training sites is more dispersed.

Risk assessment, then physicochemical and bioremediation methods can be used for cleaning up the polluted areas from the contaminants after the closure of the armed conflicts or training; however, the complexity, caused by the contaminant mixtures and the great variability of soil components, of the pollution affects the success of the procedure heavily.

Keywords: military sites, inorganic contaminants, physicochemical and bioremediation methods, armed conflict

Introduction

Nowadays, the importance of environmental protection – despite several new economic and political factors – is still high. Since the outbreak of the Russo–Ukrainian War and the freshly renewed conflicts in the Middle East, the topic of military-related environmental pollution has caught the interest of the daily news consumers. However, from

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a scientific point of view, it is a challenging field: behind the destruction of different explosives, which clearly produce significant damage in the geo- and biospheres, the released chemical agents can also play a significant role in the contamination of the natural environment.

There are several chemical components – applied mostly in the ammunition – that are dangerous for the environment. Basically, these agents can be divided into two main groups: organic and inorganic pollutants. In this article, I would like to focus on a subgroup of inorganic components, the so-called *potentially toxic elements* (PTEs), which were also known as *heavy metals*. The usage of those elements is frequent in the ordnance that leads to their higher concentrations in active and former military-affected areas.²

The potentially toxic elements and their occurrence in military-related areas

For several decades and centuries, the toxic effects of some chemical elements have been well known. Nowadays, eleven elements are defined as environmentally toxic, namely: arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), mercury (Hg), lead (Pb), manganese (Mn), nickel (Ni), selenium (Se) and zinc (Zn). However, there are more elements, such as antimony (Sb), barium (Ba), gold (Au), molybdenum (Mo), silver (Ag), thallium (Tl), tin (Sn), tungsten (W), uranium (U) and vanadium (V) that also have a negative effect on the environment.³ Most of these elements are found in ordnance, particularly in ammunition.

The most well-known element from the list above is lead. However, lead can be found in natural geological media; anthropogenic processes are important sources of pollution.⁴ Lead is a key component of ammunition (usually the bullet itself, made from it, but also found in shell fragments), which explains its common occurrence at firing ranges and in conflict zones. The concentration of lead often exceeds the permitted limits in the examined areas.⁵

Nickel, copper and zinc are the second most common metals, as they are the main components of bullet shells and can also be found in missiles, projectile fragments and coatings. These elements can be found in both residual and mobile forms in the polluted areas.⁶

Cadmium and chromium are both highly toxic elements that can be present in explosives and other military debris.⁷

However, their occurrence is less common; mercury, arsenic, antimony, cobalt and vanadium can be found in specific ammunition. According to Anastasiia O. Splodytel, mercury and arsenic are highly hazardous contaminants. While mercury can be linked to the detonation of fuses and some specific explosives, arsenic is a common

² DENTON et al. 2016; FAYIGA–SAHA 2016; TEŠAN TOMIĆ et al. 2018; SKALNY et al. 2021.

³ ALLOWAY 2013.

⁴ KORRE et al. 2002; FÜGEDI 2004; HOOKER–NATHANAIL 2006.

⁵ ALTAHAAN–DOBSLAW 2024; YASHCHENKO et al. 2025.

⁶ MOLISZEWSKA et al. 2025.

⁷ TEŠAN TOMIĆ et al. 2018; SPODYTEL 2020; PETRUSHKA–PETRUSHKA 2025.

byproduct of pyrotechnic mixtures. Cobalt and vanadium are less dangerous elements than the aforementioned ones, and their presence can be a consequence of heavy vehicle traffic.⁸

Besides the most abundant pollutants, we have to mention some emerging elements, too. Silver, bismuth, indium, tin and thallium. These contaminants are usually concentrated in industrial areas, for example smelter sites. Although their occurrence is not closely related to military activity, these metals can be released into the environment during military manufacturing processes, such as ammunition and vehicle production.⁹

Spatial distribution of potentially toxic elements in the soils of military areas

According to Nóra Szűcs-Vásárhelyi, the sources of environmental pollution can be grouped as point sources or diffuse sources.¹⁰

The military-related environmental pollution can be linked to different activities, from productive processes to training and real conflicts. Upon this approach, military-related activities should be differentiated before the application of the aforementioned source-grouping:

1. Military production plants and storage facilities: usually present at a discrete geographical place. These kinds of sources can be defined as point sources.
2. Military training sites: most commonly shooting ranges, where there are several point-like sources for the firing positions and bullet catchers. These sites are in the middle of the point source – diffuse source axis.
3. Conflict zones (e.g. Ukraine) can be expanded to several hundred square kilometres. However, there are discrete sites (e.g. damaged ammunition storage facilities) where the local concentration of pollutants is higher than in its surroundings, the whole conflict zone can be interpreted as a diffuse source.

The heavy metal contamination can be linked mostly to the impact of the artillery ammunition as well as the usage of explosives. As a result of these events, smaller fragments of ammunition reach the topsoil, from which, due to the large specific surface area of the fragments, the metals can be released into the environment.

However, the distribution of the aforementioned ammunition fragments follows the shape of the affected area. Based on the recent examinations of Liudmyla Yashchenko and her colleagues, the areas affected by the Russo–Ukrainian conflict exhibit a spherical structure in terms of contaminants.

The inner part – the direct impact/bombardment zone – is the explosion crater itself, where the highest concentrations of heavy metals are measured. In the Ukrainian example, lead, nickel, copper and manganese show significant pollution (for example, lead reached 3.9 times the maximum permissible concentration). The soil structure

⁸ SPLYDYTEL 2020.

⁹ MEES et al. 2013; LI et al. 2016.

¹⁰ SZŰCS-VÁSÁRHELYI 2019.

(soil particle size distribution), pH and humus content are also affected by the impact. The diameter of the impact crater varies between 20–100 metres.

The outer part is known as the contamination zone. This area surrounds the impact crater but is not directly affected by the exploded ammunition. The outer frontier of the zone can reach 500 metres from the centre of the impact zone. The contamination zone usually refers to the secondary accumulation area of the PTE contaminants, which may originate from small ammunition fragments and fine-grained dust released during the explosion. According to the research, the soil of this area is enriched in nickel and cadmium.¹¹

In summary, the spatial distribution of potentially toxic elements follows the geometry of the impact zone, where the most relevant contamination is characteristic of the centre, but lower concentrations can be measured in its surroundings.

Geochemical accumulation, transport and bioavailability of heavy metals

Independently from their source, heavy metals can be enriched in soils. As the PTEs are usually cationic, they can be adsorbed onto mineral surfaces of specific mineral species as well as onto soil organic matter (SOM).

Clay minerals are key components of soils. Most clay minerals are sheet silicates (phyllosilicates) that have the ability for cation exchanges in their crystalline structure. This cation exchange leads to a charge imbalance, which can be equalised via the adsorption of different (so-called *charge balancer*) cations, particularly heavy metals.

As lead, copper and zinc are the most abundant among the potentially toxic elements, their adsorption properties are well examined. Clay-rich soils, especially those whose mineralogical assemblage contains swelling clays (e.g. smectites, vermiculite), can adsorb large amounts of metal cations.¹² Besides the phyllosilicate mineral phases, iron and manganese oxides/-hydroxides also act as heavy metal adsorbents.¹³

The efficiency of adsorption depends on the pH value of the examined soils: acidic conditions usually favour lower adsorption rates in soils, which makes heavy metals more mobile. For lead, the highest experimental retention rate was observed at pH 7.¹⁴ But usually, the alkaline conditions facilitate the adsorption of heavy metals.¹⁵

Based on the above, the soil mineralogy and chemical analysis play an important role during the examination of each polluted area. Adsorption to mineral surfaces and soil organic matter, or rock layers/bodies with poor hydraulic conductivity (e.g. clays, unfractured igneous and metamorphic rocks) generally obstructs the spreading of contaminants in geological media. However, there are several ways that facilitate the extension of the pollution. Water-soluble species, like arsenic, cadmium or lead,

¹¹ YASHCHENKO et al. 2025.

¹² NÉMETH et al. 2011.

¹³ SINGH et al. 1984.

¹⁴ CHAMORRO – SÁNCHEZ-ÁNDICA 2024.

¹⁵ SIPOS 2009.

can be released easily in wet conditions and then reach deeper geological areas. Heavy rainfall – seasonal, such as the monsoon, or associated with severe weather events – supports the leaching and downward migration of pollutants.¹⁶ Ongoing climate change causes more frequent and severe storms, leading to more efficient leaching and migration of contaminants in geological media.¹⁷

When pollutants reach groundwater, spreading speed increases and a larger volume of the geological media is contaminated, including both solid and liquid phases. The worst scenarios are connected to karstic systems, where a large amount of water is present in continuous water bodies.¹⁸ Karstic systems are frequently used for irrigation and as a source of drinking water, making them one of the most vulnerable geological media.

Besides the contamination of the geo- and hydrosphere, we must not forget the atmosphere too. Due to the explosive nature of military-related sources, heavy metal-containing dust particles remain in the air for extended periods. Atmospheric currents disperse contaminants over a larger area, where heavy metals can fall onto the soil surface.¹⁹

As for contamination, exposure pathways should be determined as well. Exposure pathways are practical routes from the sources to the consumers. Bioavailable contaminants enter the food chain through plant uptake and, via a series of herbivores and carnivores, reach the final consumer: an animal or a human. In some cases, the final consumer is exposed to the contaminant directly through inhalation or ingestion. The former is common with fine-grained materials or dust, while the latter is common in polluted drinking water.

With the knowledge of the exposure pathway, the risk can be calculated. The main problem with potentially toxic elements is their bioaccumulation: most heavy metals can accumulate in mammals' organs. Lead is infamous for degenerating the nervous system. Arsenic and chromium (mostly its highly mobile form, the Cr[VI]) can cause tumours.²⁰ Most heavy metals (such as Pb, Cd, Cr and As) are linked to increased risk of cancer and reproductive disorders.²¹ Children are generally more exposed to pollution and resulting diseases.²²

Not only can mammals be affected by metal pollution, but microbial activity in contaminated soils can also change. Chronic Cd and Cr pollution reduces the microbial mass and diversity.²³ The destruction of microbial activity affects the overall health of the soil, too.

¹⁶ XU et al. 2024.

¹⁷ WIJNGAARD et al. 2017.

¹⁸ FREEZE–CHERRY 1979; DAI et al. 2024.

¹⁹ FAN et al. 2022.

²⁰ SONG et al. 2006.

²¹ MANDUCA et al. 2020; BAAH et al. 2024.

²² RAHEEMAH et al. 2025.

²³ LI et al. 2024; POPOOLA et al. 2024.

Detoxification and remediation

Serious soil contamination requires immediate intervention to halt the migration of the pollutant. There are several technical methods to achieve a clear soil from a contaminated one.

Basically, the easiest *ex situ* method is the complete removal of the polluted soil. It can work when the polluted area is shallow, the excavated soil volume is small, and no other methods can be applied. The downside of this technology is that the contaminated soil is not cleared but disposed of at a safe site as hazardous waste, and the remediated area should be covered with healthy soil from an external source.

A more sophisticated, *in situ* method is the stabilisation of the pollutant by binders, such as lime, cement or phosphate. The binders stabilise pollutants underground, reducing their leachability. This cost-effective method works well when there are no direct expositional pathways to the consumers (plants, mammals).²⁴

Chemical extraction of pollutants is an effective *in situ* technology, where the contaminated media has high permeability and conductivity (e.g. sandy soils). Chelating agents, such as the biodegradable EDDS ([S,S] – ethylene – diamine – disuccinic acid), can be used for soil washing. The washing removes metal pollutants from the soil. The method is highly effective for lead extraction from the soil of shooting ranges.²⁵

Further physical-chemical solutions, such as electrokinetic remediation or thermal treatment, are also widely applied technologies.²⁶

Beside the aforementioned detoxification technologies, bioremediation methods are also playing an important role. Compost and biochar additives also reduce the mobility and bioavailability of several heavy metals (e.g. Cd, Cu, Pb, Zn).²⁷ Phosphate amendment, as well as bamboo and rice biochars are great additives for the immobilisation of Pb and Cd. These components are reducing the plant uptake too.²⁸

Some plants can bioaccumulate high levels of heavy metals. These plants are known as hyperaccumulators.²⁹ Hyperaccumulators take up contaminants through their root systems and store them without affecting the plants' fundamental mechanisms. To date, more than 700 species, mostly from the Phyllanthaceae and Brassicaceae families, have been identified as hyperaccumulators.³⁰ These plants can be planted in polluted areas and, after some time, can be harvested with the accumulated contaminants absorbed. This method is cost-effective, but less productive than the physicochemical ones.

²⁴ DU–JIANG 2022.

²⁵ SANDERSON et al. 2019.

²⁶ HANSEN et al. 1997; ORCINO–BRICKA 1998; OTTOSEN et al. 2003; BECH et al. 2014; LI et al. 2019.

²⁷ AHMAD et al. 2012a; YANG et al. 2016.

²⁸ AHMAD et al. 2012b; LU et al. 2017.

²⁹ REEVES et al. 2018.

³⁰ YAASHIKAA et al. 2022.

Synthesis and future directions

Military-related soil contamination is a complex, persistent and globally significant problem. The diversity of the contaminants causes a large variety in the type of pollution, which can be more complex due to the knowledge of the characteristics of different soils. Remediation processes are often site-specific, based on risk assessment calculations and soil properties.

As new technologies emerge, such as shotgun-like counter-drone systems, new mixtures of contaminants are entering the environment, which should be monitored in conflict zones.

From a scientific point of view, there is a lack of long-term, field-based studies, as well as chronic laboratory tests on different trophic levels. Newly introduced industrial materials, e.g. In or Bi, have only limited scientific data on their health effects. There is also very little knowledge on the mixture of contaminants: organic and inorganic ones, or just inorganic combinations.

Ongoing armed conflicts worldwide are producing ever more data. After the closure of each conflict, it is the common responsibility of the Army and the scientific actors to make those areas clean and livable again.

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