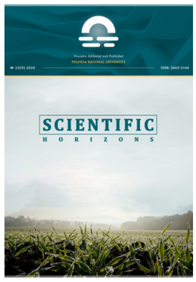
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 25(11), 92-101



UDC 504.05
DOI: 10.48077/scihor.25(11).2022.92-101

Impact of Munitions Corrosion Processes on Groundwater Contamination and Techniques for Their Safe and Cost-Effective Disposal: A Case Study of a Village

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Article's History:
Received: 10/03/2022
Revised: 11/15/2022
Accepted: 12/06/2022

Suggested Citation:
Semenenko, O., Trehubenko, S., Onofriichuk, P., Shyhyda, A., & Remez, V. (2022). Impact of munitions corrosion processes on groundwater contamination and techniques for their safe and cost-effective disposal: A case study of a village. *Scientific Horizons*, 25(11), 92-101.

Abstract. The relevance of the study lies in the fact that the ammunition that has entered the groundwater (deeper than 250 m), as a result of its disposal, poses serious threats to the entire Donetsk region water area. The purpose of the study was to investigate the impact of munitions corrosion on the aquatic environment and to consider the most effective and environmentally friendly methods of disposal. To conduct the research following scientific methods were used: methods of analysis, deduction, synthesis, and formalization method. It was found that each method of ammunition disposal led to a negative impact on the environment both in the short and long term. The literature of recent developments in munitions corrosion and munitions recycling was analyzed. It was summarized that there was an urgent need to introduce a system for cleaning up contaminated territories, to take control over the implementation of legislative environmental standards, to use new biological methods for elimination of the consequences of the impact of ammunition on the ecosystem of the region, and to switch to more environmentally friendly types of weapons. The practical value of the article is in search of ways to prevent an environmental and humanitarian catastrophe in the war zone in the East of Ukraine

Keywords: open burning, uranium, disposal, toxic substances, water and soil contamination

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INTRODUCTION

Military equipment in today's world is an important issue for all countries. However, when it is placed into the water, it leads to dangerous ecological impacts on humans and the environment. Also, most munitions are sources of mercury, filling the marine environment with its concentrations. Mostly after military equipment has been used, surplus ammunition is being dumped it into the sea, rivers and also into groundwater. The risk of explosion with this type of disposal cannot be excluded. In recent years, the impact of chemical munitions aggregate emissions, their corrosion, and their influence on public health and ecosystem has become an ever-increasing issue. Munitions contain large amounts of substances (mainly heavy metals, also trinitrotoluene (TNT) or hexanitrodiphenylamine) which can be dangerous for the environment. Corrosion processes are also the cause for the rate of ejection of hazardous materials (explosives) that may threat the aquatic ecosystem, and after all may enter the food chain, and human body during water consumption. Moreover, considering the fact that the only source of drinking water in Donetsk region is the Siversky Donets-Donbas Channel.

Also, according to the source (Using groundwater in…, 2020), there is a high content of chemical and toxic elements in groundwater in Donetsk region. Various factors influence the corrosion process. For example, the speed and rate of the process may differ depending on the time under water, and the type of munition material. The thickness and quality of coating materials are also important. When assessing the corrosion of the material, attention should also be given to the level of penetration into the sediment (Silva & Chock, 2016). Toxic substances potentially released from dumped munitions are added to the total mass of pollutants present in the aquatic ecosystem. There is uncertainty about what kind of large-scale threat humanity might face and what would be the most cost-effective methods of remediation or beneficial impacts in different disposal areas (Bełdowski *et al*., 2020). The possibility of people coming into contact with hazardous waste of military origin is now extremely high. However, there are also suggestions to find replacements for toxic substances used in munitions production to reduce the impact on the environment.

For example, in (Ferreira *et al*., 2016), the authors evaluated and equate the environmental and toxicological influences related to the life cycle of four 9 mm ammunition: a combination of two types of shells with two types of primer (lead primer; non-lead primer). Moreover, opportunities have been identified to enhance the environmental indicators of these munitions. The results showed that projectile and primer alternatives reduced exposure, mainly toxicity to humans due to the replacement of lead. However, alternative ammunition (with composite projectile) demonstrates a higher influence on ecotoxicity because of copper emissions, perhaps associated with the erosion of the projectile in the barrel of the weapon. Improper disposal of ammunition can affect a number of areas, affecting the economy of Ukraine, in particular: sea communication lines (trade); marine infrastructure, transmission through the gas lines, and oil pipelines; fishing; bases of the North Atlantic Treaty Organisation (NATO), etc. The dumping of munitions poses a direct hazard to all living things, and the degree of the threat depends on the condition the hazard sources themselves have been in for as long as they have spent in a corrosive water environment (Miętkiewicz, 2020).

Alboloushi *et al.* (2020) studied the environmental pollution situation in the Gulf of Kuwait as a result of military operations in the Persian Gulf region in 1991. Scientists determined that only natural uranium remained in the seawater, while depleted uranium has not been detected. It is thus clear that even in the case of the decomposition of uranium-containing munitions, it is possible to for the ecosystem to fully from radioactive substances, although this requires some time. The study by Beck *et al.* (2022) examines the damage from munitions that have been present in the coastal waters of the southwestern Baltic Sea since the two world wars. Scientists claim that from explosives contained in munitions, marine biota accumulates toxic elements. Biota is food for larger marine life, such as commercial fish species (flounder). Even outside the munitions dump, TNT was found in the fish. At this stage, the toxic substances in marine inhabitants consumed by humans do not pose a threat to health and life, but researchers focus on the continued corrosion of the walls of munitions, which will significantly increase the number of harmful substances in coastal waters and organisms that live there.

Scharsack *et al.* (2021) in addition to studying the effects of munitions in marine waters considered climate change as one of the reasons for the increased harmfulness of toxic substances to marine organisms. Wars are not only a danger to the environment, but also a danger to the habitat. Global warming entails a chain of other climate changes that can lead to environmental disasters. In the face of massive storms, typhoons, and volcanic eruptions, the corrosion of munitions in the water will accelerate exponentially, as will the overall damage from the toxins entering the water. However, there is a positive trend in this process: due to an increase in the temperature of the water, the process of processing biota chemicals munitions will be significantly accelerated. Zhang *et al.* (2021) team also investigated the environmental impact of depleted uranium munitions, but the burials were not in water but in soil. The focus of the study was to establish a link between the toxicity of munitions and soil moisture levels. The corrosion started in corner cracks, edges, and small pits of ammunition, and accelerated with increasing soil moisture. The results of this study show the influence of soil moisture on the corrosion rate and the migration rate of DU metal.

A. Souchen (2022) conducted a study on the process of disposing of the Canadian state of surplus ammunition and military equipment used in World War II. The need for disposal triggered three main reasons, among which are the post-war recycling crisis, the desire to prevent deflation of the economy, and the unprofitability of leftovers. Military materials were processed and used in the production of products for a peaceful life. The positive side of the policy was also negative: often the prices of reproducible products were overvalued and sales were artificially reduced. Ferreira *et al.* (2019) in their research proposed an alternative model of ammunition processing, which has a much smaller impact on the environment. Scientists speak about the use of energy material in ammunition in the production of explosive materials for civilian use. This approach to recycling is seen as a replacement for the usual combustion processes in complex waste incineration plants, as it has limitations on the capacity of the incinerator, electricity consumption, and high cost.

Thus, *the purpose of this research* is to address the environmental issue associated with ammunition dumping in groundwater. The study also considers the impact of progressive corrosion of notorious munitions and analyses safe and cost-effective methods of disposal.

MATERIALS AND METHODS

Within the framework of this study, the features of the Donetsk region were studied as an example of a region of active hostilities. The data to create the work was collected between 2019 and 2021. As research methods, articles in scientific journals from such databases as ScienceDirect, Science, Nature Publishing Group, Taylor and Francis, Science, and SpringerLink were analysed. Ukrainian news portals were also used, providing open sources and data on the state of groundwater, issues of drinking water for the Donetsk region population, and questions about the imminent disposal of unsuitable ammunition for the storage of new batches. Through the media, it was possible to identify the main health concern of the Donetsk region population – the lack of clean drinking water and the impact of military action on the population. The Ukrainian Ministry of Defence, together with the British charity and American non-profit organisation HALO Trust, demonstrated a map (Figure 1) of Donetsk region with information on areas contaminated by mines and explosive remnants of war (The Ministry of Defense presented..., 2018). The marked bright circles indicate how the terrain is filled with munitions, minefields, etc. The "cleanest" spaces are mostly in the eastern and Western parts of the Donetsk and Luhansk regions, making the results in ammunition disposal methods considered to be of concern to this area on account of their safety. Furthermore, the disposal requires underground and buried storage and landfill sites away from the public and potentially unsafe areas. In Ukraine, an ammunition recycling programme was already introduced in 2008-2017, where 474 thousand tons of ammunition had to be processed. To conduct the research following scientific methods were used: methods of analysis to identify the main toxic materials from the munitions in the region; deduction to assess the level of the environmental danger of such toxic materials for the villages; synthesis to select the most effective ways to minimize a negative influence to the Donetsk and Luhansk regions` water ecology; and formalization method to illustrate the corrosion and dissolution of depleted uranium processes as a chemical expressions.

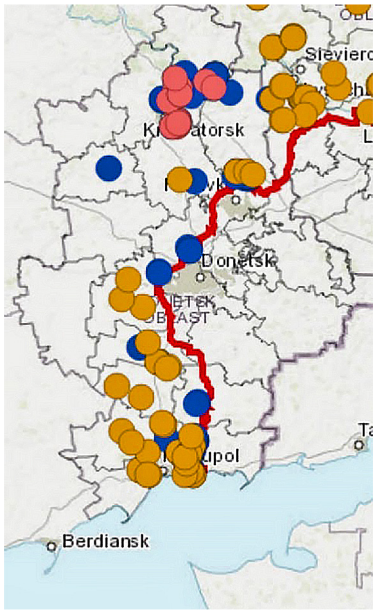

***Figure 1**. Donentsk and Luhansk regions territory information map*
***Source:** The Ministry of Defense presented..., 2018*

The following section is divided into two main stages where important aspects of the study are addressed. Firstly, the process of munitions corrosion and its impact on water, the environment and the population were considered. Studies listing the elements that can be formed by ammunition corrosion have been cited. Such elements include: uranium (including its oxides), mercury, lead, copper, tungsten, arsenic, and zinc. All of these elements can have negative consequences and affect human health and vital activity and environmental safety. This paper also reviewed studies in analysing the behaviour of munitions corrosion in water in general, including oceans, sea, rivers, groundwater, etc., as the species of bacteria found in oceans, freshwater, etc., are very similar.

The second stage dealt with the area of ammunition disposal methods. Classifications were given and the latest innovative technologies proposed by various authors, such as thermal salt recovery, oxidation, solvent extraction, biodegradation, alkaline hydrolysis and green technology, were listed. When searching for keywords related to this work, the results show a number of concerns expressed by the population of Donetsk region regarding a large amount of ammunition disposal, military activities and flooding of mines, which have a detrimental impact on livelihoods. The cited case studies can be used as a basis for further investigations. All of the analysed studies involving ammunition disposal can be implemented at any location.

RESULTS AND DISCUSSION

Corrosion of ammunition. In the traditional classification, two types of underwater ammunition are distinguished: those that contain dangerous elements and those that do not. Hazardous elements are various types of detonators, explosives, chemical warfare agents, and fuses. When items are thrown with a specific purpose during an event, they are defined as detonators and are classified as Unexpected Ordnance Disposal (UOD). Corrosion of ammunition in water occurs due to the flow of environmental, electrochemical, and microbiological processes. First, there is an ejection of soluble metal cations (electrolyte) and the passage of electrons through the metal, to the neighbouring cathode sections of the metal surface. Here the consumption process happens, due to which the amount of diluted oxygen and water molecules at the cathode is reduced in order to form hydroxide ions. The electrochemical cell obtained as a result of the described process leads to corrosion of the solid metal at the anode sites. This is because of the ejection of metal ions into the mud, due to which localized holes are formed on the surface, and the reaction products of soluble metal cations and hydroxide anions are also precipitated. The described process has the form of amorphous metal hydroxides and oxyhydroxides in neighbouring large cathode surfaces. The described process is called general or "homogeneous" corrosion. The overall corrosion rate is determined by the presence of dissolved oxygen and the level of electron consumption that occurs during the reaction to ensure charge balance (Silva & Chock, 2016). Sulphide-reducing bacteria (SRB) found in waters should be investigated very carefully, just like bottom sediments. Due to them, biofilms form on metal surfaces, which can make the corrosion process more difficult. This process is called microbiologically influenced corrosion (MIC). The intensification and potential of corrosion processes are determined by the presence of such bacteria and their populations (Cybulska *et al.*, 2020).

The improvement of military hardware and the increased usage of projectiles with urbanisation disrupt infrastructure development. However, the removal of ammunition can be fraught with technical risks that may cause even greater harm and threat to the environment, and in some cases, for example, for large unexploded ordnance, it is considered an impracticable option using currently available disposal methods. Donetsk region has a single source of water supply – the Siverskyi Donets River. In the research (Nikolopoulou *et al.*, 2022), the authors assessed the pollution of this artery. Patterns of new pollutants along with nutrients and metals have been explored in surface water and groundwater samples. The results thus show that warfare and mine flooding have had harmful impact on the population. This requires groundwater pumping to avoid the ingress of toxic substances into the groundwater, at the very least, and also to avoid groundwater seepages. Previously, groundwater has already been investigated by means of an ecological-geological survey in the Donetsk region at a distance of 30 km from Donetsk (Water of questionable quality…, 2019). The results showed that all elements of the periodic table were present in the soil. This is already a sign that corrosion together with improper disposal has significantly affected the environment. For example, in the village of Yaremivka, the results of water analyses show high levels of nitrates along with sulphate shale (Special project, 2021). Negative results are also shown near Toretsk and in the village of Novhorodske – the samples contain high salinity, which already implies that it is no longer suitable for drinking (JCCC: Toretsk threatens…, 2017). It is also worth noting that in the village of Solnetsvka, as in many other villages in the region, there is no centralised water supply, residents complain about water quality, which is confirmed by the results of analyses (Humenyuk & Nazarov, 2018).

For villages in Donetsk region, there is no other water source than the Siversky Donets-Donbas (Dangerous water and soil…, 2019), and given that all groundwater is saturated with toxic elements, it cannot be used. Ignoring this issue will lead to an environmental catastrophe, the consequences of which cannot be reversed. In work Bełdowski *et al.* (2019) the results show that flooded munitions in the water are sources of mercury deposited as bottom sediments. Bełdowski *et al.* (2016a) investigated the disposal site of chemical munitions within the Gotland Basin. The findings suggest that the analysed area may be characterised by huge number of objects and that these sediments might contribute to the spreading of pollutants in the bottom sediments. Military training activities, especially those involving munitions, can have a negative impact on the surface soil as they deposit metals such as Pb, Sb, Cu, As, Zn and W that pose risks to human health and the safety of the environment. Military projectiles mainly consist of a steel penetrating element, followed by a Pb/Sb bullet coated with a Cu, Zn and Pb alloy shell (Barker *et al.*, 2021). However, it is important to consider that the toxic, weakly radioactive element uranium U is widely used in munitions during wartime conflicts. Flooded uranium is a co-product of the Uranium-235 fortification process, which is used in nuclear reactors and weapons. The production of 1 kg of fuel from enriched uranium containing 235U yields approximately 5 kg of depleted uranium waste. Depleted uranium is used in many areas, such as in counterweights for aircraft, in the capacity of catalysts in the oil and gas sectors and for radiation protection. Depleted U is thermodynamically volatile and thus prone to corrosion in the natural environment. The corrosion and dissolution of depleted uranium occur as follows:

$$U_{(s)}+2H_2O \rightarrow UO_2(s)+2H_2 \quad (1)$$

$$U_{(s)}+O_2 \rightarrow UO_{2(s)} \quad (2)$$

$$UO_{2(s)}+2H^{+}+\tfrac{1}{2}O_2 \rightarrow UO^{2+}_{2(aq)}+H_2 \quad (3)$$

$$UO_{2(s)}+2H_2O+\tfrac{1}{2}O_2 \rightarrow UO_3 \cdot 2H_2O_{(s)} \quad (4)$$

$$UO_3.2H_2O_{(s)}+2H+ \rightarrow UO^{2+}_{2(aq)}+3H_2O \quad (5)$$

The level of depleted uranium corrosion is much higher in water than in the air. However, the content of water in the soil influence on the erosion mechanism of depleted uranium, but it is important to consider activity parameters such as soil pH. Thus, it was shown by Lotufo *et al.* (2021) that the corrosion level of depleted uranium was influenced by the soil's water content. From the perspective of influence on soil micro- and macrofauna, depleted uranium corrosion causes a marked decrease in the variety of the microbial community. In the material written by Papageorgiou *et al.* (2022) there are samples from groundwater have been examined and the results show that approximately 10% of the groundwater has a uranium concentration exceeding the World Health Organization provisional norm of 30 μg/l for drinking water. Explosions of depleted uranium release particles of uranium oxide, such as UO_2 and UO_3, which spread into the air for about 10 km, thus increasing the contamination radius with long-lasting effects on animals, insects, water, food and air. The study conducted by M.R. Joyce and K.H. Holton (2020) outlines four possible ways of ingestion: inhalation of depleted uranium powder, swallowing through infected food products and liquids, shrapnel injuries or dermal suction of dust. The same data are reported by the author of the research work "Metals/Metalloids: Environmental Exposure and Health Effects" (Danesi, 2019) – depleted uranium weapons leave fragmented or undamaged penetrating particles along with dust, which, if inhaled, are highly likely to be acquired, especially by persons spending some time in vehicles affected by the ammunition. All the studies carried out so far showed that exposure doses in the open air were so low that they did not pose a significant risk. For those spending at least 10 hours a year in vehicles affected by depleted uranium munitions, the risk of fatal cancer is slightly higher (~0.2%).

Plaza *et al.* (2018) report that ammunition is an underestimated source of lead. That is, pollution by lead through bioaccumulation and lack of biodegradation should be expected to become a worldwide issue that affects the health of all living beings. Lead is extremely toxic for humans, and the presence in food of the rest emissions could be very dangerous for health. T. Schupp (2021) investigated areas where relatively high Pb inputs to soil had previously been observed. The results show that such areas require long-lasting groundwater monitoring, even if Pb accumulation is considered insignificant. In the work created by Straumer *et al.* (2020) the relationship between impact of fish to dumped munitions and histopathological changes in the liver is investigated. Fish from the "reference (clean) site" showed less pathology compared to those from the area where munitions were disposed of. The study of corrosion products from the decomposition of ammunition, which have been under water for more than 60 years, was carried out by Li *et al.* (2016). To conduct the study, scientists used various technologies, including EDXA (energy dispersive X-ray spectroscopy) combined with XRD (X-ray structural analysis) and Raman spectroscopy. β-Fe2(OH)3Cl together with Fe3O4 and β-Fe OOH – this is how the primary phase was determined after treatment of the inner layer. The researchers found a thick layer of nodule that was outside the iron hydroxychloride layer. The nodule layer consisted of an outer greyish-white layer of CaCO3 and an internal black layer of FeCo3. The authors of the study attribute the formation of FeCo3 to the exchange process of Fe2+ ions with Ca2+ ions in the CaCO3 layer. The exchange process occurred during the movement of Fe2+ ions to the external coral sheet from the corroding steel.

Findings of Bełdowski *et al.* (2016b) show that dumped munitions can degrade to inorganic arsenic and that the disposal areas studied contain high levels of arsenic compared to the reference areas. Thus, the materials that make up ammunition are generally highly susceptible to oxidation and corrosion (e.g., uranium is highly sensitive to hydrogen, oxygen, carbon and nitrogen), which requires preventive treatment. The dissolution of harmful substances in water is considered an important, first stage in their decomposition. Corrosion of munitions refers to a phenomenon in which the object itself and the environment are subjected to chemical, electrochemical or physical attack, resulting primarily in deterioration of the environment and the release of toxic substances. Preventing and controlling such a situation means that methods and technical measures for prevention and long-term protection must be applied, based on a study of corrosion principles and the reaction mechanism of munitions in the environment. In worst-case situations of chemical weapons corrosion, specific instructions on how to avoid contact or how to handle military items need to be developed. The presence of munitions on sediments also adversely affects cables, main gas and oil pipelines, etc.

Groundwater is an important component of the natural water cycle. It connects the Earth's surface and surface receiving waters. The Earth's population, fauna and flora, i.e., its entire environment, attract negative consequences due to the pollution of groundwater and soil through the corrosion of munitions. The groundwater of Donetsk region has poor water quality. It can no longer be used as a drinking source. It is directly involved in the process of leaching ammunition parts, which forms a plume of contamination. The speed of the corrosion process and extrication all of the chemical and toxic materials later are depend on the conditions in which the munition lies. Usually, the oxygen and entraining current encourage the destruction of the weapons. That is, the corrosion of the munitions and the associated possible leakage into oxygen-containing layers of water and sediments leads to a diffuse release of the explosive substances and chemical warfare agents they contain. Conventional munitions, especially those containing trinitrotoluene, are poisonous to microorganisms and aquatic vegetation.

That is, different toxic substances are released during the corrosion process, depending on the ammunition material. When water contacts with the toxic substances, it could be a dissolvent or suspending substance. Therefore, chemicals seep into the ecology system, initially spreading pointwise, probably entering into an equilibrium process of sorption/desorption in sediments and eventually spreading more widely because of water processes and humans' activities. Ingestion and inhalation of corrosion products are potential routes of radiation exposure. Thus, drinking water and consuming food contaminated with the substances listed above is harmful to human health. It is therefore worth focusing on the purity of groundwater used for public consumption. Also, as effective measures to reduce the entry of such toxic substances into the soil, measures should be taken to reduce their Pb content, and the use of depleted uranium in ammunition construction should be banned. Munitions require corrosion protection methods and techniques at all stages: design, construction, operation and disposal.

Disposal of ammunition. The most common and long-standing methods of ammunition disposal are:

1. Open burning is one of the most common disposal methods, carried out in especially remote locations (e.g., military landfills). The process is carried out as follows: the ammunition is burned on the ground using fuel. The combustion temperature does not exceed 500°C, there may be residues of waste products.

2. Open detonation is also a frequently used method of disposal, but there are some limits to its applicability. The process is carried out by detonating the munition with an explosive charge, resulting in the complete chemical decomposition of the object, but particles of heavy materials may remain, which are detrimental to the quality of the air and soil.

3. Closed detonation, similar to the open detonation method, but with the advantage of controlling emissions to the environment (Zhu *et al*., 2021).

Ammunition storage, and its safe disposal at Ukrainian military bases, is a pressing issue. Pavlograd Chemical Plant is one of the leading enterprises in Ukraine engaged in ammunition disposal. The company contributed to the development and implementation of integrated processes for the disposal of ammunition, which have a favourable impact on the country's economy, and the development of recycling technologies for material resources such as metals, plastics, etc. Zhu *et al.* (2021) presented a detailed study on the dangers of six different methods of ammunition disposal. The results showed that the closed detonation method brought about the highest hazard and the highest risk, followed by open burning and open detonation. There are also disposal methods that have been used for quite a long time. The basic principles of such techniques are briefly outlined below. The mechanical disassembly method (designed for large calibre ammunition) – the idea is to separate the shell from the casings using pulling machines or by breaking them out. Disposal method using an electric arc, i.e., the direct impact of an electric arc on a cartridge case, with further destruction of the ammunition cartridges. The firing method has advantages such as security, cost-effectiveness, etc. An electric incinerator is the most economical yet effective method of disposing of munitions. Its high efficiency in handling ammunition is due to the fact that the disposal process is fully automated for small arms and has a reserve of recyclable material from individual items (casings, shell casings, etc.). Moreover, the operation of this furnace is not dangerous for the personnel (Yang *et al*., 2019).

At each stage of the munitions manufacturing process – production, transport, storage, distribution and disposal – environmental degradation occurs through the introduction of explosive contaminants in the form of pure liquid or solid particles due to leaching, trace particles, contaminant spills, fully or partially detonated and unexploded munitions. Wastewater from ammunition is generated during the production and disposal of ammunition containing residual energetic substances. Despite the necessity of removing energy pollutants from munitions wastewater, practical treatment faces three obstacles. The first obstacle is that energy substances are biochemically unstable. The second is that the physiological destruction of these nitro elements releases nitrates (NO_3-) and/or nitrites (NO_2-), which causes secondary contamination. The third obstacle is that such substances usually coexist in the wastewater of ammunition and must be removed. The study by Zheng *et al.* (2022) has succeeded in developing a technology that is two to three orders of magnitude superior to other methods. The authors of another study (Pirzadah *et al*., 2022) propose a method of phytoremediation, which involves the inherent ability of plants to bind these explosive compounds in their original forms or to modify and decompose them into inert forms. In response to the need for safe disposal, plasma arc technology with the ability to safely dispose of munitions in an environmentally acceptable manner is given in work created by Gonçalves *et al.* (2022). This technology has been installed and operated in the Western District, North Carolina since 2001.

Thermal saline disposal, solvent extraction, oxidation, alkaline hydrolysis, and biodegradation are becoming more and more common as new methods of ammunition disposal. The alkaline hydrolysis method can rightly be considered the most popular among all the above mentioned approaches. This method is the removal of nitro groups from nitrocellulose, followed by the formation of nitrites and nitrates. The formation of the latter becomes possible due to the course of chemical reactions such as substitution and hydrolysis (Li *et al*., 2019). S.A. de Oliveira *et al.* (2018) compared the influence of three ways of disposing of ammunition on the environment. Among the three methods analysed were open blasting; a combination of incineration including the air pollution control, open burning, recuperation of some energy materials, and recycling of the metal; burning in a stationary incinerator with control of the air pollution level combined with the recycling of metal. The results indicate that the biggest impact is the recycling of munition and minimizing the extending of air pollution after incineration. The lowest degree of satisfaction with disposal tasks was traced as a result of the open detonation.

Corrosion processes are now also taking place for metal shells of ammunition once thrown into the water. It is impossible to determine the exact duration of the complete completion of the corrosion process. However, complete corrosion has a number of disadvantages. For example, it is very difficult to determine the fact of lost ammunition due to the absence of metal cases as such. Or high levels of chemical release from decomposition into the environment. Also, one should not ignore the change in climatic conditions, which reduces the possibility of predicting the future fate of the ammunition being dropped to zero. The solubility of the object, water temperature, oxidation, and hydrolysis are of paramount importance in determining the bioavailability and continued residence of chemicals in the water, which as a result can affect the ecosystem as a whole. The location of the munitions dump is also a fact that deserves attention, as it has certain environmental parameters, similar to the types and quantities of chemical and conventional munitions dumped. The creation of a monitoring system by drilling deep wells at the disposal site can solve the problem of monitoring the state of groundwater pollution.

It is also worth considering the possibility that explosive residues could be washed away by rain, which would affect groundwater. This issue can also be solved by the introduction of treatment plant systems. However, the popular physical and chemical approaches to cleaning up polluted areas are costly. There is a growing trend of munitions waste management towards the use of 'green' technologies that will benefit water, soil, etc. One such alternative is the plant and microbe clean-up method, which has the benefits of being low-cost, highly efficient, environmentally friendly and also cost-effective. Microbes are unique, characterised by versatile and prolific decomposition functioning systems that promote favourable degradation and recycling of toxic substances as energy resources, adapting well to changes in the environment. Plants absorb harmful substances from groundwater and are subsequently converted.

There are two categories of green technologies with which it is possible to dispose of toxic substances that are contained in the soil. The first one is ex situ technologies (with soil removal). The second is known as in situ technologies (without soil removal). The bioremediation processes of the first technology require the extraction of soil that has been contaminated or the extraction of groundwater that has been contaminated. The in-situ technology makes it possible to process contaminated objects directly at their location. S. Anand & S.M. Celin (2017) demonstrated the positive results of an attempt to use microbes in the purification process, including them in ammunition. The safety of the process of neutralizing toxic materials using this technology was ensured. The gradual reduction process of TNT, which resulted in the formation of hydroxy-amino-dinitrotoluene ($C_7H_7N_3O_5$), 4-amino-2, 6-dinitrotoluene, 2-amino-4, 6-dinitrotoluenes, various azox compounds, 2, 6-aminonitrotoluenes and 2, 4-diaminonitrotoluenes, was preceded by the inclusion of the bacterial organisms Pseudomonas putida GG04 and Bacillus SF in the munitions. The latter process was carried out in order to improve the bioremediation of 2, 4, 6-trinitrotoluene remains. A description of the experience of using plants during processing is also present by Zheng *et al.* (2022).

Thus, the use of “green” technologies is popular, effective, and most importantly environmental in the disposal of ammunition for cleaning from toxic substances. Microbes are widely used in the restoration of heavy metals on contaminated sites. This technology is expected to gain traction and displace chemical processes, but a further extensive investigation is needed to achieve this. Such techniques need to be introduced into Donetsk and Luhansk regions, as much of the area is already occupied by minefields and munitions, making disposal difficult. While all disposal options have advantages and disadvantages, they must be preceded by a thorough risk assessment, both of the potential proliferation of the munitions and of the consequences of the various disposal options.

CONCLUSIONS

The widespread and significant effects of soil contamination due to munitions waste from military operations in Donetsk and Luhansk regions contribute significantly to the global loss of productive soils and landscapes. The danger posed by the dumping of munitions in groundwater from various quarters should be considered. The accumulation of harmful substances in different parts of the food chain, as well as their direct toxicity, should be considered in the risk assessment to the same extent as the adverse effects of direct exposure to substances. The study found that industrial processes, military activities, disposal processes using old methods such as open burning, open detonation, and the release of munitions in inappropriately designated areas generate and release large quantities of explosive and toxic substances. The discharge and detonation of these explosive chemicals pose a danger to natural resources and living beings, polluting the soil and groundwater. The study also has pointed to the underestimation of the disposal of munitions, leading to the conclusion that the issue until now has been poorly studied and remains overlooked. The lack of studies on conventional munitions can be a serious obstacle to further risk assessments for humanity. Underestimating the issue can have unpredictable environmental and economic consequences.

Donetsk and Luhansk regions need to introduce a system of monitoring and cleaning the condition of the soil, and groundwater. State programmes must be implemented, considering the selection of areas outside of military operations, and wellfields. Each method of ammunition disposal leads to a negative impact on the environment both in the short and long term. Therefore, it is important to pay attention to the method of treating the effects of munitions disposal using plants and indigenous microbes. Successful use of "green" technological concepts will reduce the risks to the environment and the population of Donetsk region. The studies on the replacement of ammunition calibres with more environmentally friendly calibres are also worth paying attention to. This requires the following measures to be taken: reduction of energy required for production; replacing traditional cartridges (which use brass) with plastic, cardboard or, eventually, using ammunition without cartridge cases; replacing copper and nylon as materials for the composite projectile.

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Вплив процесів корозії боєприпасів на забруднення ґрунтових вод і методики їхньої безпечної та економічно вигідної утилізації: аналіз прикладів села

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Анотація. Актуальність дослідження полягає в тому, що боєприпаси, які потрапили в підземні води (глибше 250 м), в результаті їх утилізації, створюють серйозні загрози для всієї акваторії Донецької області. Метою роботи було дослідити вплив корозії боєприпасів на водне середовище та розглянути найбільш ефективні та екологічно безпечні методи їх утилізації. Для проведення досліджень були використані наступні наукові методи: методи аналізу, дедукції, синтезу та метод формалізації. Встановлено, що кожен метод утилізації боєприпасів призводить до негативного впливу на навколишнє середовище як у короткостроковій, так і в довгостроковій перспективі. Проаналізовано літературні джерела останніх розробок з питань корозії боєприпасів та утилізації боєприпасів. Узагальнено, що існує нагальна потреба у впровадженні системи очищення забруднених територій, запровадженні контролю за виконанням законодавчих екологічних норм, використанні нових біологічних методів для ліквідації наслідків впливу боєприпасів на екосистему регіону та переходу на більш екологічно безпечні види озброєнь. Практичне значення статті полягає у пошуку шляхів запобігання екологічній та гуманітарній катастрофі в зоні бойових дій на Сході України

Ключові слова: відкрите спалювання, уран, захоронення, токсичні речовини, забруднення води та ґрунту