

Integration of Processes of Radionuclide-Contaminated Territories Decontamination in the Framework of their Ecological-Socio-Economic Rehabilitation

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ABSTRACT

Large-scale disasters at nuclear power plants (NPPs) and their consequences are still the subject of discussion by the world scientific community, which makes mankind recognize the unsolved problem of radiation pollution. Accordingly, the search for new effective biocomposite materials with high sorption capacity to eliminate harmful effects associated with radiation contamination of large territories is an urgent task on a global scale. This paper is devoted to the study of the decontamination processes of the areas contaminated with radionuclides, the search for new mechanisms of fixation of radionuclides and heavy metals in the soil using the matrix material of different origin. In order to intensify the process of radionuclide fixation in the soil-plant system the method consisting of introducing into the soil the organic-mineral biocomposite based on sewage sludge and phosphogypsum after anaerobic fermentation was proposed. It is necessary to further study the processes of sorption and radionuclides solubilization due to complexation with organic agents present in matrix materials of different nature. The mechanisms of radionuclide and heavy metal fixation using matrix material of different origin were analyzed and a general model was formed. The direction of integration of radionuclide-contaminated soil decontamination technologies into the process of ecological, social, and economic development of the territories under rehabilitation after the accidents at the Chernobyl NPP and Fukushima-1 NPP is proposed.

Keywords: radionuclides, heavy metals, mechanisms of fixation, biocomposite materials, soil restoration, rehabilitation of contaminated territories.

INTRODUCTION

The environmentally sound development of territories exposed to radiation contamination is a key issue not only for individual countries but also for the world community within the framework of the sustainable development concept implementation.

The impact of radiation on human health and the environment was widely discussed after the

accident at the Chornobyl nuclear power plant. Radiation in the form of radionuclides that enter the human body through water, food, soil, air, has a dangerous property to accumulate and irradiate the body. An important property of soils is their sorption capacity, which directly depends on the amount of organic matter and silt particles in the soil, which contribute to the fixation of radionuclides.

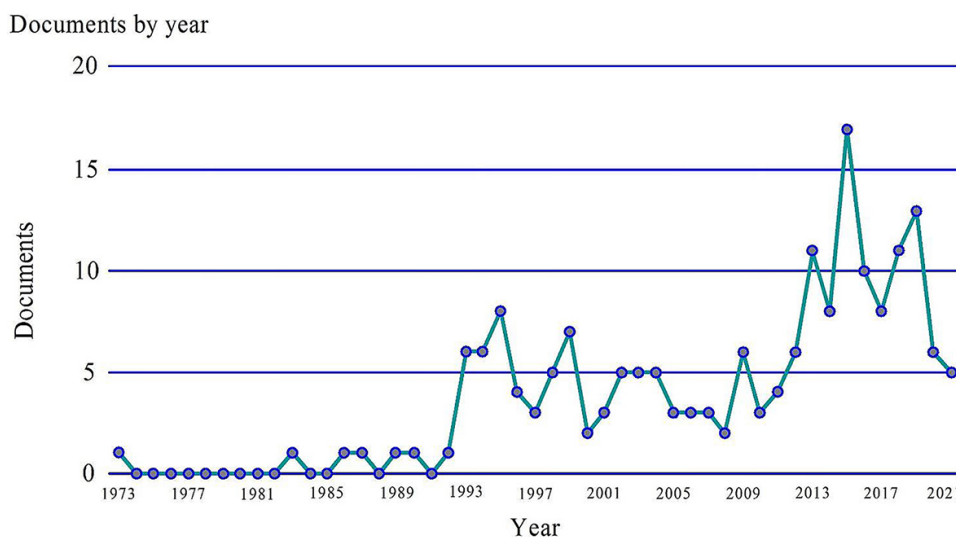


Figure 1. Publication activity by years in editions of Scopus indexed databases when setting a combination of keywords «soil and decontamination and radionuclides»

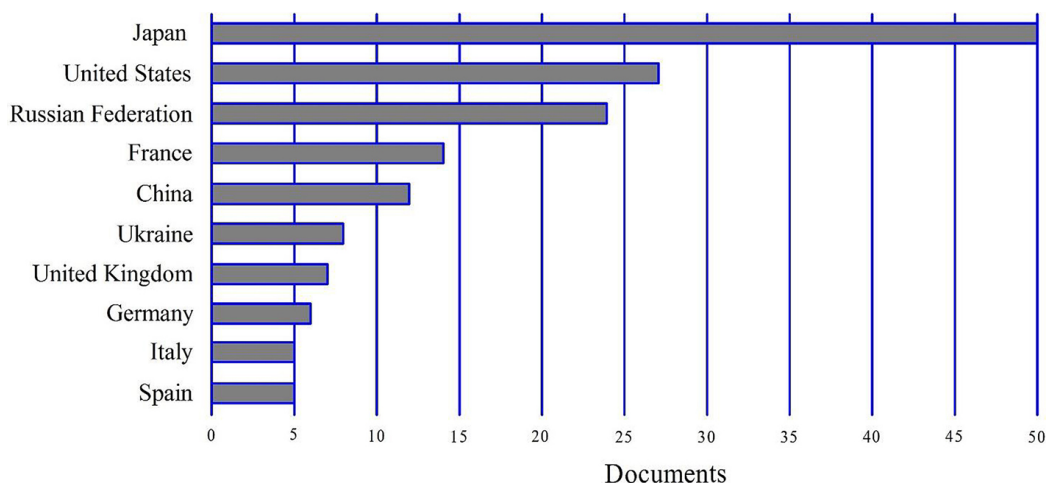


Figure 2. Publication activity by country according to the Scopus database

According to the dynamics of publication activity in the context of research on the decontamination of soils contaminated with radionuclides, peak activities by years of the most large-scale disasters at nuclear power plants are traced. At the same time, it is worth noting the cooperation of different countries in the field of radiation management of the territories recovering from the accidents at the Chernobyl and the Fukushima-1 nuclear power plants.

Over the last twenty years, various technological methods of sorption and accumulation of toxic substances have been widely developed, which allow localizing radioisotopes and ions of heavy metals and prevent their migration in soil, surface, and groundwater [Jioa et al., 2021; Kang et al., 2021; Kojima et al., 2006].

Despite significant progress in this area, the task of improving the selectivity and sorption

capacity of known types of materials is still relevant and there is a great need for new composite materials, especially those that have high efficiency of disinfection of solid materials, including soil complex, and suitable for the removal of harmful effects associated with radiation pollution of large areas after accidents at nuclear facilities.

Basic processes that create a radioecological situation (redistribution, deposition, migration) take place in natural systems or are formed under the influence of natural factors. From this point of view, the barrier function of the exclusion zone is realized through the control of objects and processes that play a significant role in the deposition and migration of radionuclides. The total stockpiles of radionuclides in the Chernobyl Exclusion Zone (taking into account those available at the Shelter facility) are estimated by scientists to be

about 350 PBq. However, the amount of radionuclides that are most likely to be included in the removal processes outside the Chernobyl Exclusion Zone is much smaller. This is mainly the territory of the Zone and the Temporary Localization of radioactive waste. Migration from the largest radionuclide depot to the Chernobyl Exclusion Zone (Shelter) was millionths of percent and did not exceed 0.012 TBq/year, while the minimum water removal was defined as approximately 4 TBq/year [Chernysh et al., 2021].

The long-term development of the Chernobyl Exclusion Zone is an important and complex task that must account for various technical, economic, social, and other factors; various ideas concerning the development of this zone were considered. The final decision on permitting the return of the population to this area should be made considering the uneven contamination of land, specific characteristics of migration of radionuclides and their accumulation in different segments of the local landscape, as well as traditional habits of the population living in the region (hunting, fishing, and mushrooms, etc.).

More than 1 million tonnes of contaminated water has accumulated at the Fukushima Daiichi nuclear power plant since it was struck by a tsunami in March 2011, triggering a triple meltdown that forced the evacuation of tens of thousands of residents. Tokyo Electric Power (Tepco) has struggled to deal with the buildup of groundwater, which becomes contaminated when it mixes with the water used to prevent the three damaged reactor cores from melting. Tepco has attempted to remove most radionuclides from the excess water, but it is the most difficult to rid the water of tritium, a radioactive isotope of hydrogen [<https://www.theguardian.com/environment/2019/sep/10/fukushima-japan-will-have-to-dump-radioactive-water-into-pacific-minister-says>]. In addition, since $\approx 75\%$ of the surface affected by the highest levels of ^{137}Cs deposition in Fukushima Prefecture is forested and not decontaminated, the potential long-term contribution of radiocesium to the river systems draining these typhoon-prone mountainous, forested landscapes should be investigated. The behavior and dynamics of longer-lived radionuclides, such as plutonium isotopes, remain poorly documented and should also be studied in the future as they can persist in the environment for a long time, even if they were released at trace and ultra-trace levels [Evrard et al., 2019].

The study of the distribution of radionuclides and heavy metals, their mobility, as well as bioavailability under the influence of variable factors and environmental conditions, is a necessary factor for the restoration of contaminated soils. The potential migration of radionuclides is of concern to contaminated land and, in the long term, waste storage facilities.

Thus, the purpose of this work is to substantiate the directions of integration of the decontamination processes of the soils contaminated with radionuclides in the integrated development of territories after accidents at nuclear power plants and their ecological, socio-economic recovery, considering the sustainable development goals. Accordingly, to solve this goal, the following research tasks were formed:

- review and substantiation of the mechanisms of fixation of radionuclides and heavy metals when using matrix material of various origin;
- integration of technologies for decontamination of the soils contaminated with radionuclides into the process of ecological-socio-economic development of territories recovering from the accidents at the Chernobyl and the Fukushima-1 nuclear power plants.

THE METHODOLOGICAL BASIS FOR DECONTAMINATION OF SOILS CONTAMINATED WITH RADIONUCLIDES AND HEAVY METALS

Strengthening the barrier functions of the Chernobyl Exclusion Zone involves solving several issues, as shown in Figure 3.

Table 1 shows that for the immobilization of radionuclides of groups of alkaline and alkaline-earth elements, as well as halogens, the main rock-forming minerals (frame aluminosilicates) are better suited, while the use of accessory minerals (phosphates, titanates, and titanium zirconate) [Kojima et al., 2004]. Thus, phosphates, zirconolites, and sphenes can be recommended for use as matrix materials.

The introduction of organic-mineral complexes on the soils contaminated with radioactive substances should be carried out according to carefully balanced schemes and taking into account the specificity of soil differences. If the use of almost all types of fertilizers leads to higher yields and causes a decrease in the content of radioactive substances in plant products on fertile loamy soils, then on light by mechanical composition, low-mineralized,

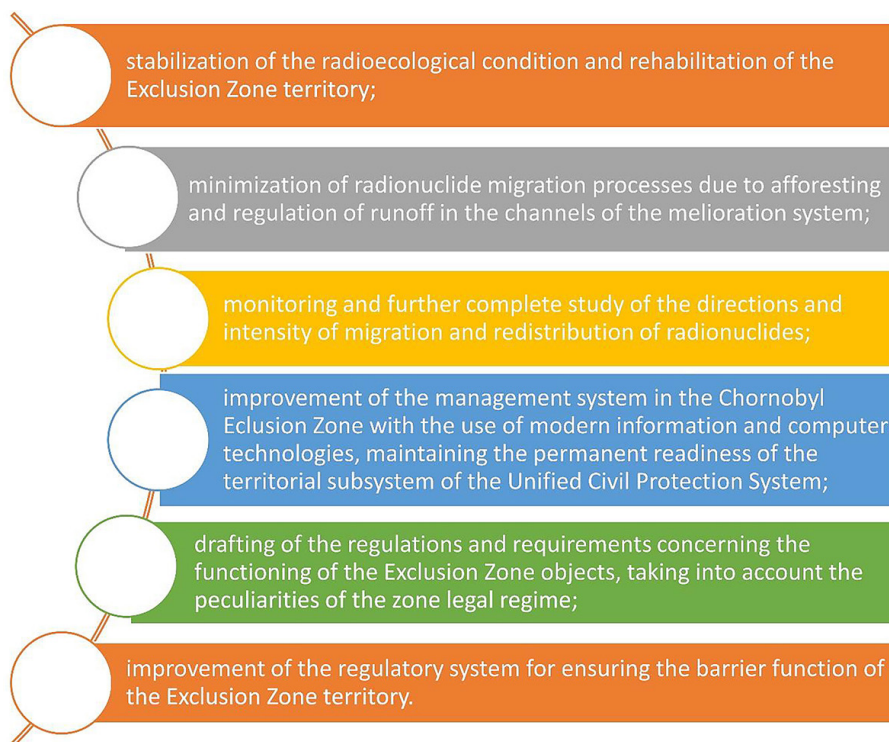


Figure 3. A set of tasks to optimize the functioning of the Exclusion Zone

Table 1. Minerals-Potential Concentrators of Radioactive Elements

Mineral	The formula of the mineral	Radioactive waste element isomorphically fixed in minerals
Feldspar	$(\text{Na, K, Ca})(\text{Al, Si})_4\text{O}_8$	Ge, Rb, Sr, Cs, Ba, La...Eu, Tl
Nepheline	$(\text{Na, K})\text{AlSiO}_4$	Na, K, Rb, Cs, Ge
Sodalite	$\text{Na}_8\text{Al}_6\text{Si}_6\text{O}_{24}\text{Cl}_2$	Na, K, Rb, Ge, Br, I, Mo
Olivine	$(\text{Fe, Mg})_2\text{SiO}_4$	Fe, Co, Ni, Ge
Pyroxene	$(\text{Fe, Mg})_2\text{Si}_2\text{O}_6$	Na, Al, Ti, Cr, Fe, Ni
Zeolites	$(\text{Na, Ca})[(\text{Al, Si})_n\text{O}_{m+k}] \cdot x\text{H}_2\text{O}$	Co, Ni, Rb, Sr, Cs, Ba
Perovskite	$(\text{Ce, Na, Ca})_2(\text{Ti, Nb})_2\text{O}_6$	Sr, Y, Zr, Ba, La...Dy, Th, U
Apatite	$(\text{Ca, REE})_5(\text{PO}_4)_3(\text{F, OH})$	Y, La...Dy
Monazite	$(\text{REE})\text{PO}_4$	Y, La...Dy, Th
Sphene	$(\text{Ca, REE})\text{TiSiO}_5$	Mn, Fe, Ni, Sr, Y, Zr, Ba, La...Dy
Zirconalite	$\text{CaZrTi}_2\text{O}_7$	Sr, Y, La...Dy, Zr, Th, U
Zircon	ZrSiO_4	Y, La...Dy, Zr, Th, U

hydromorphic soils we can expect an increase in some of them when applying mineral fertilizers. It remains relevant to study new types of organic and organic-mineral fertilizers that can be effectively used to increase the stability of the soil-plant system while utilizing various types of waste as components of these complexes.

In order to increase the level of fixation of radionuclides in the soil, it is proposed to use an organo-mineral biocomposite based on sewage sludge after anaerobic conversion, together with dihydrate phosphogypsum, which was studied in previous works [Chernysh, et al., 2019; Plyatsuk, et al., 2014].

The mineral composition of silt sediments was studied to understand the forms of binding of metals and organic substances. As a result of the analysis of X-ray diffraction spectra, the information on the forms of metals in the silt sediments was obtained and their phase distribution was determined. The main compounds of the mineral component were identified, among which one can distinguish [Chernysh et al., 2019; Plyatsuk et al., 2014]: quartz – SiO_2 ; iron compounds in the form of iron phosphate hydroxide – $\text{Fe}_4(\text{PO}_4)_3(\text{HO})_3$; compounds of aluminum and silicon in the

Although this method proved to be effective for the first type of soil, it is not for the second. In particular, lime must be added to adjust the pH of the Andisols after acid treatment and must be mixed with untreated as well as uncontaminated soil before reusing it for growing soil. In addition, additives such as zeolite or Prussian blue adsorbents must be added to Andisols to avoid the transfer of residual radioactive cesium to plants. The problem with this strategy is that, as a result of exploitation, zeolites can increase the exchangeability of ^{137}Cs with potassium and accelerate the transfer of ^{137}Cs into crop plants for longer periods [Yamaguchi et al., 2019]. These limitations show the difficulty of finding the alternatives to storing waste of decontaminated soil at intermediate sites.

A further study of the solubilization process of radionuclides through complexation with organic agents that are present in mixed radioactive waste and radioactively contaminated land of natural and anthropogenic landscapes is required. The interaction of complexing agents with radionuclides and the environment, as well as the reactions of changes in physicochemical environmental conditions that affect the mobility of heavy metals and radionuclides, are the processes that require a scientific and theoretical basis. In addition, chemical degradation and biodegradation of organic materials may also be important for understanding the migration and accumulation of heavy metals and radionuclides. When environmental conditions change, the distribution of pollutants also changes, which leads to an increase or decrease in their mobility. The study of such dependencies is the theoretical basis for the development of methods for their mobilization-immobilization. In addition, the search and development of appropriate solid and liquid matrix materials and composites are fundamental to the justification of these technologies.

Over the past twenty years, various technological methods for the sorption and accumulation of toxic substances have been widely developed, which make it possible to localize radioisotopes and heavy metal ions as well as prevent their migration in soil, surface, and groundwater [Hu et al., 2008; Norrfors et al., 2016; Payne et al., 2013; Plyatsuk et al., 2013; Runde et al., 2002].

Thus, the task of improving the sorption ability of known types of materials is still

relevant and there is a high demand for new composite materials, primarily having high disinfection efficiency for solid materials, including the soil complex, and also being suitable for the elimination of the harmful effects associated with radiation pollution of ecosystems.

The interaction of pollutants with the soil matrix and their interaction with environmental variables are important for the transport and proportion of mobile radionuclides, as well as for determining the environmental risks for living organisms. The absorption of radionuclides by soil can occur through various methods of interaction, while other mechanisms are responsible for their removal from the organo-mineral matrix.

The incorporation of trace elements into calcite has a great influence in many areas of environmental chemistry and geochemistry. The generalized model for justifying the transition from adsorption to co-deposition of heavy metals and radionuclides in the mineral complex was created and shown in Figure 4 according to previous works [Chernysh et al., 2019; Chernysh et al., 2020].

The model was developed based on the natural mechanisms of sorption and ion exchange that occur in the mineral structure of soil horizons under the influence of natural factors, such as partial pressure, temperature, organic component, depth of the aquifers, evaporation and capillary characterization bound water as an elastic solid.

The introduction of phosphogypsum into the sludge during anaerobic conversion contributed to the introduction of additional macrocarrier-analogs into the organic-mineral structure of sediments. Note that the introduction of phosphorus and calcium compounds contained in phosphogypsum intensifies the process of fixation of heavy metals and radionuclides in sewage sludge. Therefore, it was revealed in the mineral component of sewage sludge after anaerobic fermentation of the compound hydrogen of calcium phosphates and potassium, which are capable of sorbing radionuclides. It was also assumed that the radionuclides and heavy metals released into the solution are immobilized by enzymatic reductive deposition, biosorption, and redistribution in a stable mineral phase to the biocomposite. Such components of biocomposites as Ca, Fe, K, Mg, released into the soil solution, become available for plants.

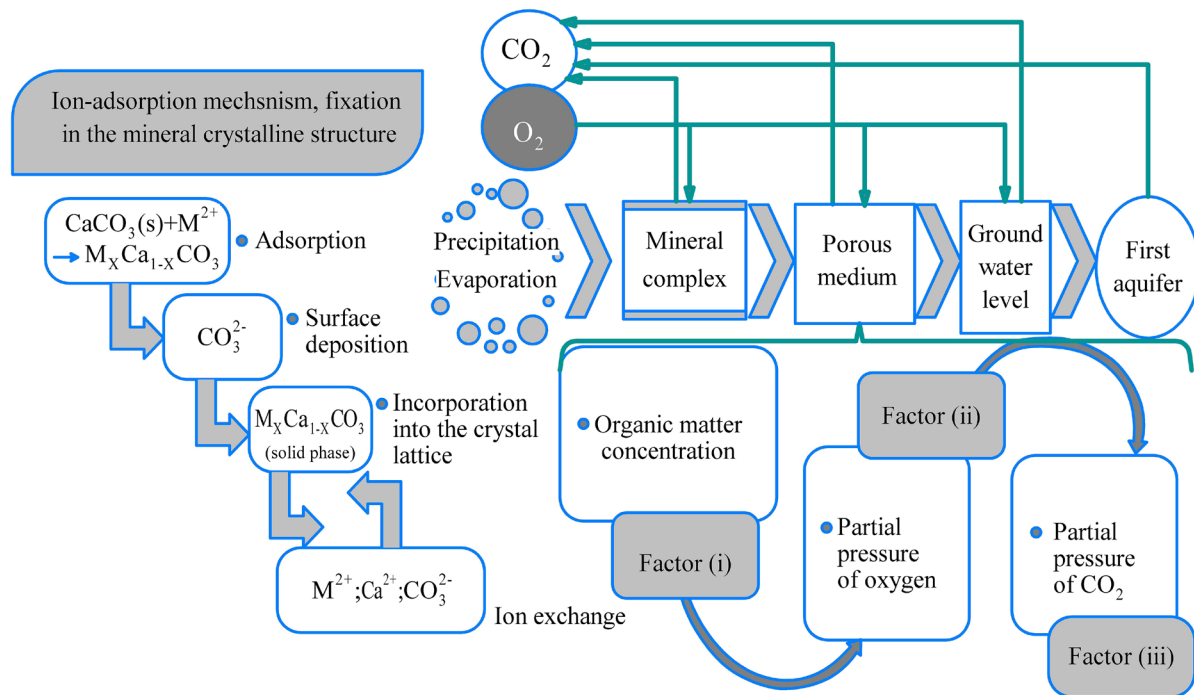


Figure 4. The processes of mobilization and accumulation of dissolved substances during infiltration with a description of the mechanisms of metal fixation (M) in the mineral component of the organo-mineral complex

INTEGRATION OF TECHNOLOGIES FOR SOILS DECONTAMINATION UNDER ECOLOGICAL-SOCIO-ECONOMIC DEVELOPMENT OF TERRITORIES RECOVERING

For 2015–2020 within the framework of eight large-scale projects of the United Nations Development Program (UNDP) and partners, more than 25 initiatives were implemented with a total budget of more than 4 million US dollars [Tihonov, 2015] in the following areas:

- sustainable urban infrastructure and energy efficiency;
- environmental protection;
- education;
- health care and active longevity;
- tourism and local entrepreneurship;
- waste processing (including hazardous waste);
- horticulture and sustainable agriculture, including organic.

UNDP Belarus has established a network of regional coordinators, which has an important potential to forge sustainable partnerships with local non-governmental organizations and bring together development efforts in the affected areas.

The Chernobyl Investment Platform has been designed as a unifying infrastructure element to support the development of 21 regions

of southeastern Belarus. The platform will bring together the efforts of a large number of participants – government, business, civil society organizations, academic institutions, UN agencies, donors, and, as a result, citizens – to develop and implement the projects based on local, effective, and promising ideas and solutions (Figure 5) [Tihonov, 2015].

Chernobyl Investment Platform will help generate innovative partnerships, business initiatives, and solutions; explore the application of best available technologies, governance and financing models, including green finance and green solutions, create new jobs and develop local economies, which will contribute to the achievement of the sustainable development goals.

The main functional and structural elements of the platform:

- regional information and analytical center for providing support to small and medium-sized enterprises, which will ensure digitalization of entrepreneurship.
- resource center for applied areas of adaptive physical culture, physical rehabilitation, occupational therapy, and information technology.
- engineering and technological consulting center for the development of sustainable entrepreneurship in the regions affected by the Chernobyl accident, which will provide.

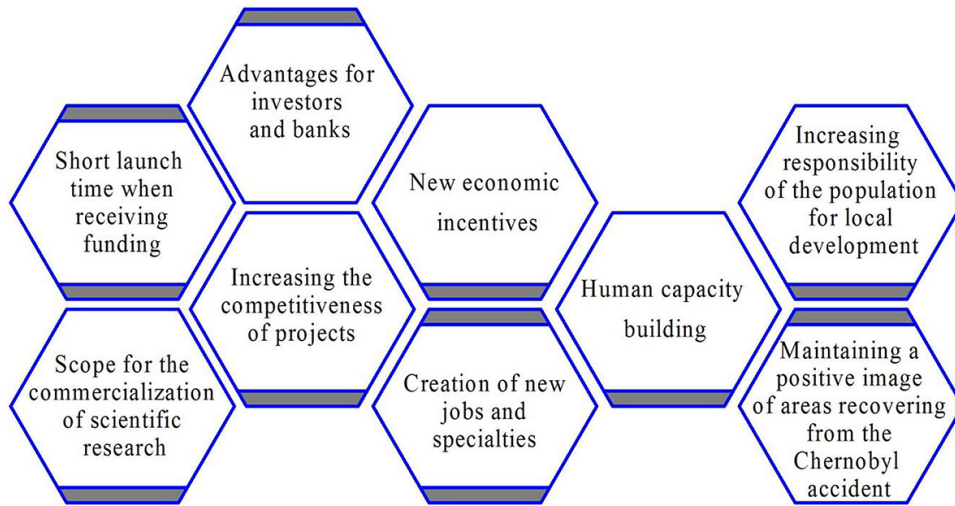


Figure 5. Benefits from coordinated development of areas recovering from the Chernobyl accident. Based on [https://www.by.undp.org/content/belarus/ru/home/presscenter/blog/Chernobyl_investment_platform.html]

The functionality of the engineering center should provide:

- the scientific and technological adaptation of the existing solutions to the needs of small and medium-sized enterprises in the region;
- development (support for the creation) of new technological solutions to solve the problems of small and medium-sized enterprises in the region;
- providing engineering and scientific and technological consultations (services) to small and medium-sized enterprises in the region;
- support for the implementation of scientific solutions and technologies that will ensure the reclamation and restoration of the land fund affected by the Chernobyl accident.

Accordingly, the choice and regional adaptation of soil decontamination technologies will be an integral and basic task of the engineering center of the Chernobyl investment platform.

That is why the experience of Japan is important for the study and analysis, where various strategies were implemented to decontaminate the soil on agricultural land: either by removing the contaminated soil layer or by sowing the plants with the ability to extract and concentrate radio-caesium from the soil. The contaminated soil, removed as a result of the decontamination work, is transported to an intermediate storage point, where flammable decontamination waste is incinerated or melted to reduce its mass and volume.

A generalized block diagram of soil decontamination after an accident at the Fukushima-1 nuclear power plant was formed and shown in Figure 6.

Depending on the radiocaesium content, these wastes are either stored in an intermediate storage facility or disposed of at a solid waste landfill with leaching control [Evrard et al., 2019]. The main stages of the technological process are indicated in Figure 7.

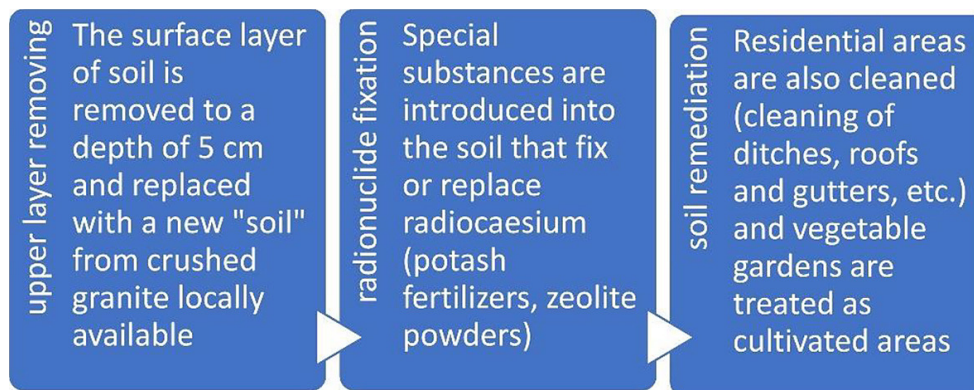


Figure 6. Block diagram of soil decontamination processes based on the experience of implementing technical and reclamation measures in the area of the accident at the Fukushima-1 nuclear power plant

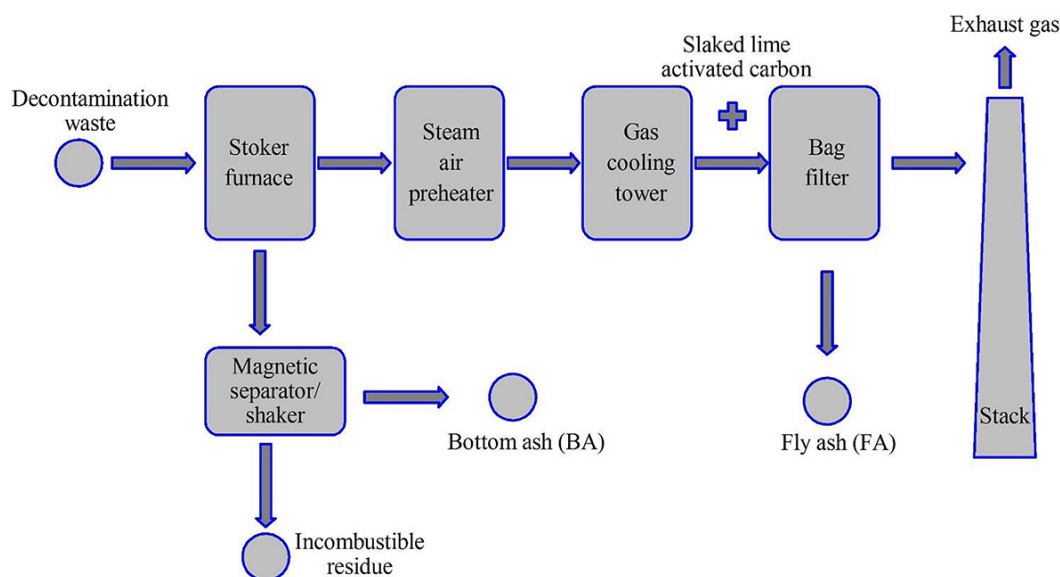


Figure 7. Flow diagram of an incinerator handling decontamination waste in Fukushima Prefecture (Japan) [Evrard et al., 2019]

The soil storage operations began in October 2017 in Okuma and in December 2017 in Futaba, Japan. By March 2019, ≈ 2.5 million m^3 of soil waste had already been transported from temporary storage facilities distributed throughout the reclaimed area to these two temporary storage facilities [Japanese Ministry of the Environment, 2021a]. All soil waste is planned to be transported to the Okuma and Futaba landfills by the end of 2021 [Japanese Ministry of the Environment, 2021b]. The final disposal of this decontamination waste should take place outside the Fukushima Prefecture within 30 years after the opening of the temporary storage facility (≈ 2047). In cultivated landscapes where restoration work has been concentrated, the main question is whether to resume agricultural production. Removing the topsoil that concentrates radiocesium, replacing this material with crushed granite from local quarries, and finally mixing the entire profile to prepare the soil for re-cultivation, raise several important questions. For example, the study [Evrard et al., 2019] was indicated the following emerging problematic issues during the decontamination of lands in the impact zone of the Fukushima-1 nuclear power plant: to what extent the residual radiocesium in the soil will migrate to the plants grown on these soils, and how strongly will the crushed granite after homogenization with soil affect its fertility?

Accordingly, in the authors' opinion, the use of a complex of composites for the

decontamination of radiation-contaminated soils and the restoration of their fertility is the primary task of the ecological-socio-economic development of the regions recovering from the accident at the Chernobyl nuclear power plant and the Fukushima-1 nuclear power plant.

Thus, studies of various types of preparations of modified composition are being carried out, which can be used in a complex manner for decontamination and restoration of the soils contaminated with radionuclides and/or heavy metals. Figure 8 shows several examples of such hybrid composites, which in general can be classified according to the following principles:

- organo-mineral composites produced based on physicochemical and biochemical transformations of the initial (secondary) raw materials;
- mineral support (granular) modified with various chemical compounds for the sorption of heavy metals and/or radionuclides with the possibility of forming a bi-film of rhizosphere microorganisms on it;
- biological products containing immobilized groups of microorganisms in a gel-forming reagent with mineral additives;
- specifically targeted sulfur-containing preparations of biogenic origin, the composition of which is close to gaseous sulfur, obtained chemically using the Claus reaction and redox processes, with the inclusion of microbial biomass, complex use is possible as a component of fertilizers.

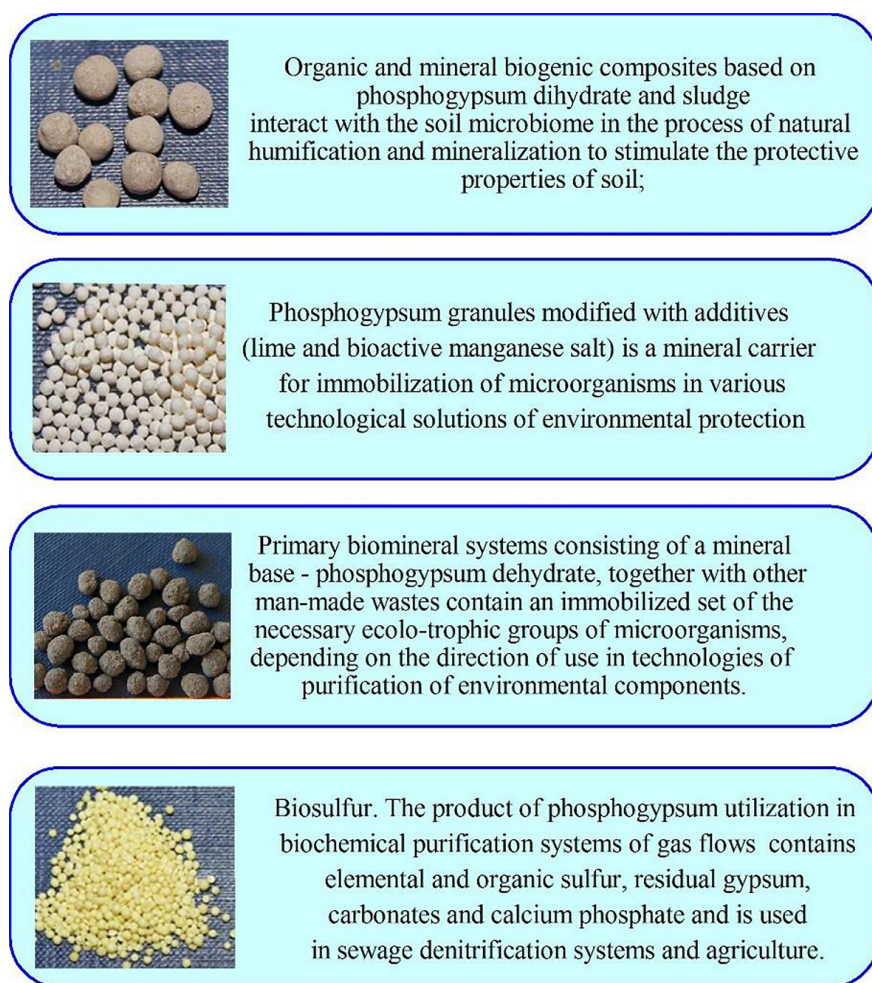


Figure 8. Development of biogenic composites containing transformation products of phosphogypsum, by groups of component composition. According to previous research [Chernysh et al., 2020; Chernysh et al., 2021; Plyatsuk et al., 2018]

It should be noted that the formation of organo-mineral compositions in bioprocesses of fermentation of sewage sludge from urban wastewater treatment plants, together with phosphogypsum, can be intensified during the primary treatment of the liquid phase using AOPs technologies, which requires further research to obtain the compositional composition of such organo-mineral preparations (essentially digestates in the process of anaerobic fermentation), as well as an additional environmentally friendly energy resource, which can be considered as one of the directions of decarbonization of the industry.

A generalized scheme of the factors affecting the migration of radionuclides in the ecosystem, and the influence of the organic-mineral complex on the fixation of radionuclides in soils was formed and shown in Figure 9.

The increase in exchange capacity is usually due to an increase in the sorption strength of the microquantity of radionuclides, and the

composition of exchange cations determines the specifics of exchange reactions of radionuclides with their chemical analogs-macrocarriers concerning these radionuclides. For example, the accumulation of ^{90}Sr by plants in most cases is inversely proportional to the absorption capacity of the soil and the amount of exchangeable Ca and for ^{137}Cs -K. As noted, the entry of radionuclides into plants and their accumulation in the crop is largely determined by the content in the environment of their chemical analogs. As the amount of calcium and potassium in the soil or nutrient medium increases, the supply of ^{90}Sr and ^{137}Cs to plants decreases [Chernysh et al., 2018; Smičiklas et al., 2016].

The introduction of phosphogypsum into sludge sediments during anaerobic fermentation was facilitated by the introduction of additional macronutrient analogs into the organo-mineral structure of sediments. Note that the introduction of phosphorus and calcium compounds contained

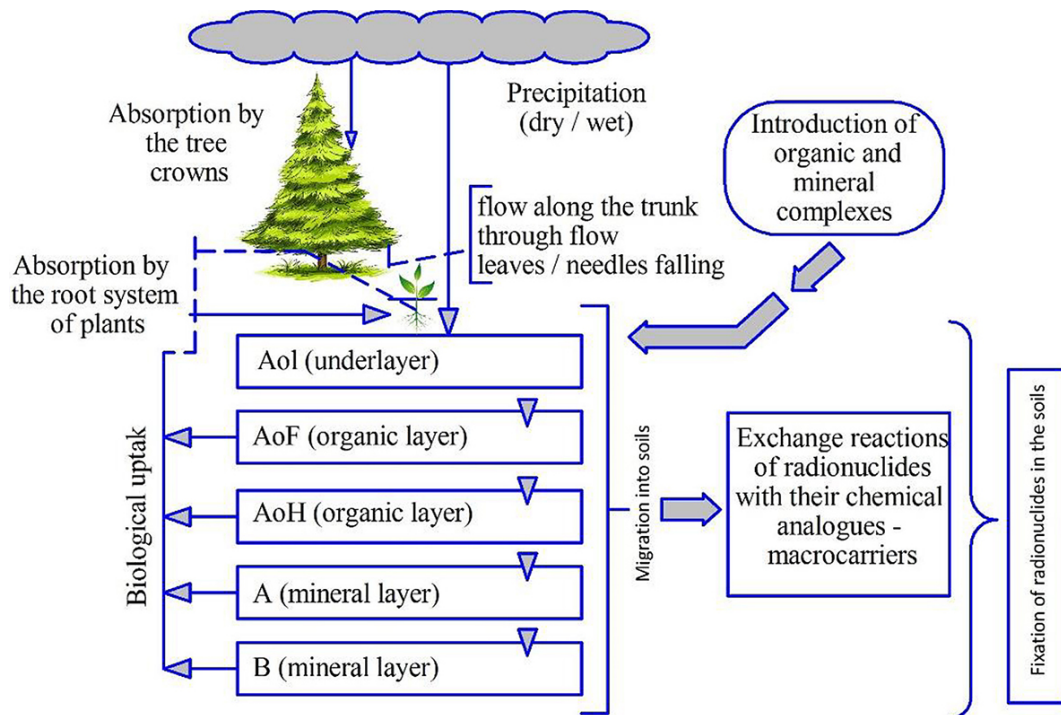


Figure 9. Influence of organo-mineral complex on the fixation of radionuclides in soils

in phosphogypsum intensifies the process of fixation of heavy metals and radionuclides in sludge. Thus, calcium and potassium hydrogen phosphate compounds, which can sorb radionuclides, were found in the mineral component of sludge after anaerobic fermentation.

At the same time, the threat of catastrophes caused by global problems is increasing. The world practice of their elimination shows that the efforts

to respond to emergencies are becoming more expensive and ineffective. Two schemes (Fig. 10 and 11), which reveal the principles of functioning of the two systems of counteraction to emergencies at agricultural enterprises through the «water supply» channel were formed. The existing technologies and means of liquidation of emergencies at industrial enterprises and agricultural firms operate on the principle: recording of a negative effect→

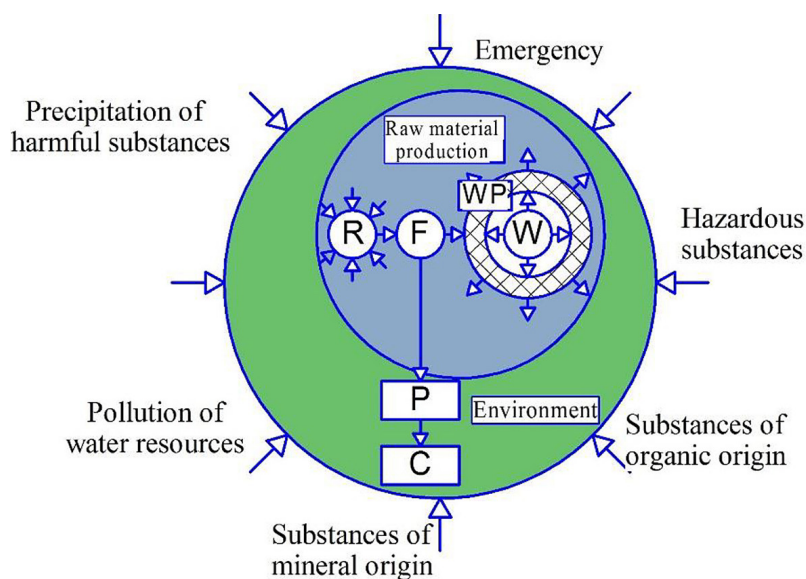


Figure 10. The traditional scheme of counteraction to emergencies at agricultural enterprises through the «water supply» channel: R– raw; F – farm; P – product; C – consumer; W – waste; WP – waste processing (aqueous solutions)

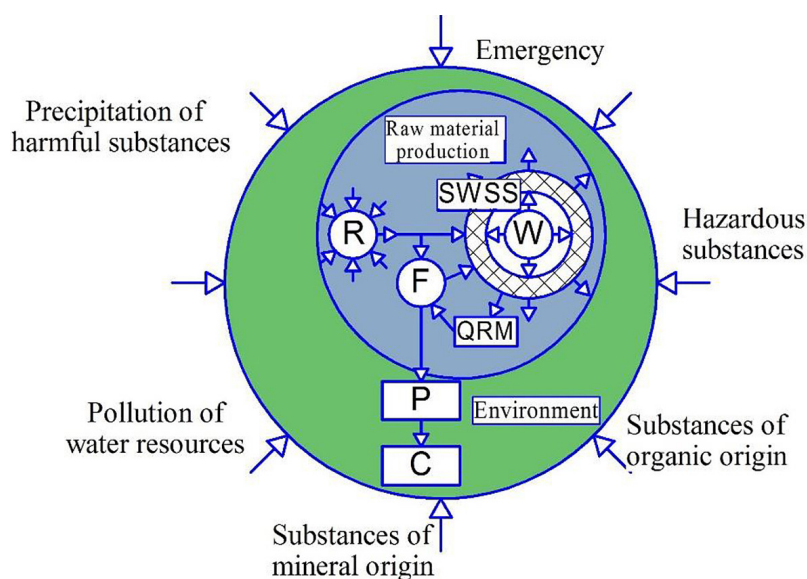


Figure 11. Environmentally safe scheme to prevent emergencies in agricultural enterprises through the «water supply» channel: QRM – quality raw materials; SWSS – safe water supply system

equipment installation → neutralization (Figure 10). The main disadvantage of such a system algorithm is that during the time from detection to disposal of harmful substances, people, animals, territory, etc. can be polluted (as an example of the accident at the Chernobyl nuclear power plant) and technological processes can be stopped. The threat also exists for the agricultural enterprises where there was no direct infection. It can occur through transport, raw materials, etc.

It is obvious that under the current environmental conditions it is necessary to radically change the functional scheme of agricultural enterprises, including in the affected areas. It must anticipate emergencies in advance (Figure 11).

From an economic point of view, installation of new technological equipment should be better in terms of resource and energy efficiency than the previous one.

CONCLUSIONS

The search for the latest composite materials that would neutralize the negative effects of radionuclides and solve the problem of environmental pollution remains an urgent task for modern science. According to the results of the study conducted in this article, the main mechanisms of fixation of radionuclides and heavy metals by introducing organo-mineral composites based on sewage sludge and phosphogypsum after anaerobic fermentation were considered and substantiated,

and the mineral composition of sludge was analyzed for more effective binding of metals and organic substances. It was established that the introduction of organo-mineral complexes in the areas contaminated with radionuclides should be carried out according to balanced schemes and taking into account the specificity of soil diversity. The study identified the main directions aimed at decontamination of soils contaminated with radionuclides in the process of ecological, socio-economic development of the areas that are recovering from the Chernobyl and Fukushima-1 accidents. The key areas are the use of a set of composites for decontamination of radiation-contaminated soils and the restoration of their fertile layer; decontamination of soil on agricultural lands by removing the contaminated layer of soil or by sowing the plants that can extract and concentrate radiocaesium from the soil; minimization of radionuclide migration processes through the implementation of afforestation measures and ensuring the regulation of runoff in the channels of the reclamation network; development of normative-legal base concerning the functioning of objects of a zone of alienation taking into account the features of a legal mode of this zone.

In connection with the theoretical substantiation above, the authors consider it important to conduct further research in the following directions:

- to determine the degree of purification of soils from cesium, strontium, and cobalt radionuclides, reduction of secondary soil contamination, statistical processing of

results, and construction of an appropriate regression model of efficiency of fixation of radionuclides and heavy metals in soil decontamination processes;

- creation of a new systematic approach to the functioning of economic entities at both regional and strategic levels.

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