

EREM 77/2 Journal of Environmental Research, Engineering and Management Vol. 77 / No. 2 / 2021 pp. 43–52 DOI 10.5755/j01.erem.77.2.28633	Integrated Approach of Phytostabilization for Urban Ecosystem Soils Contaminated with Lead	
	Received 2019/06	Accepted after revision 2021/03
	 http://dx.doi.org/10.5755/j01.erem.77.2.28633	

Integrated Approach of Phytostabilization for Urban Ecosystem Soils Contaminated with Lead

Tetiana Yakovyshyna*

Prydniprovsk State Academy of Civil Engineering and Architecture 49600, Ukraine, Dnipro, st. Chernyshevsky, 24a

*Corresponding author: t.yakovyshyna@gmail.com

The article discusses the creation of a methodological approach and the specific technologies based on it in terms of the phytostabilization of urban soils contaminated with heavy metals, taking into account the peculiarities of urban ecosystems functioning in order to ensure the environmental safety of industrial wastelands. Based on the analysis of existing soil restoration methods, a mechanism for creating an integrated phytostabilization technology was developed by involving the components differing in action, aimed at reducing the migration ability of heavy metals in soil and their translocation into plants. It was suggested to increase the phytoremediation potential of phytostabilizers through the stimulation of internal defence mechanisms of plants, and through additional application of an ameliorant to bind heavy metal cations in soil, as well as through the use of microbiological preparation in order to restore soil protective functions. The practicability of phytostabilization using alfalfa (*Medicago sativa*) plants combined with detoxification with an aqueous solution of potassium carbonate and the BTU-r multipurpose biocomplex microbiological preparation was experimentally confirmed by means of an example of lead contamination of urban ecosystem soils in the city of Dnipro. It was concluded that their combination provides the lowest Pb^{2+} removal from the soil by alfalfa (*Medicago sativa*) plants and a significant reduction in the availability of the metal compounds in soil.

Keywords: heavy metals, phytostabilization, soil, urban ecosystem, contamination.

Introduction

Phytostabilization involves the use of plants that are resistant to heavy metals, making them unavailable/inactive in soils through sorption, precipitation, complexation or chemical reduction (EPA, 1997; Erakhrumen & Agbontalor, 2007; Erdei 2005), individually, but these are more efficient when combined with changes in soil properties, in order to limit the bioavailability of metals. In addition, the cover formed from phytostabilizing plants provides protection against erosion and heavy metals leaching into groundwater under flushing regime (Fagnano et al., 2020; Tang et al., 2019).

Traditionally, the phytostabilizing plants can be found through systematization of wild species growing on soils with excess content of heavy metals, followed by the analysis of their distribution in plant organs (Cetinkaya & Sozen, 2011). At phytostabilization, the plant species should have a greater ability to accumulate metals in the roots, while their transfer to aerial parts tissues is very limited (Fagnano et al., 2020); therefore, such plants can be potentially consumed by living organisms (Vangronsveld & Cunningham, 1998). There are even a number of crops that can be grown on contaminated soils without any risk to human health (Yakovyshyna, 2011).

However, based on the analysis of phytoremediation potential, it has been discovered that the phytostabilization effect is largely inherent in wild flora species; for example, in terms of lead pollution, the plant species acting as phytostabilizers are listed in Table 1.

It should be noted that some scientists consider phytostabilization as a containment technique unable to solve the problem of heavy metal pollution, but it only aims at reducing their availability, and therefore their toxicity to plants, so it can only be used as an intermediate measure (EPA, 1997).

The difficulties of phytostabilization method implementation are related to its complexity, the amount of biomass produced, the depth of root system and its branching, the chemical properties of particular soil and its contamination level, the plant age, concentration and characteristics of pollutants (for example, the content of available (extraction of ammonium acetate buffer solution (AAB), pH 4.8) and potentially available (1 n HCl) forms of heavy metals), as well as climatic conditions, primarily the amount of precipitation, affecting their availability (Tangahu et al., 2011).

Table 1. Plants-phytostabilizers of the soil contaminated with the Pb

Plant	Comment	Reference
<i>Lygeum spartum</i> (L.), <i>Piptatherum miliaceum</i> (L.), <i>Limonium sinuatum</i> (L.)	Plant survey	Conesa et al., 2006
<i>Schinus molle</i> (L.), <i>Euphorbia</i> sp.	Plant survey	Gonzalez and Gonzalez-Chavez, 2006
<i>Brassica carinata</i>	Plant survey	Irtelli et al., 2006
<i>Atriplex lentiformis</i>	Greenhouse study using compost	Mendez and Maier, 2008
<i>Atriplex canescens</i>	Field study	Rosario et al., 2007
<i>Amaranthus hybridus</i> L.	Plant survey	Salas-Luevano et al., 2007
<i>Triadica sebifera</i> (L.), <i>Hibiscus cannabinus</i> (L.), <i>Corchorus capsularis</i> (L.), <i>Ricinus communis</i> (L.), <i>Populus nigra</i> (L.)	Field study	Tang et al., 2019
<i>Panicum miliaceum</i> L.	Field study	Yakovyshyna, 2014

In the urban ecosystem conditions, there may be additional problems arising in relation to a significant diversity of soil formations (urban soils of various types, technosols, sealed soil, necrosols, etc.), which, in turn, will result in a variability of agrophysical, agrochemical, ecological and biological properties of soil, as well as those related to the characteristics of the urban ecosystem itself, for example, the degree of environmental footprint, the availability of associated pollutants influencing the availability of heavy metals, and to the functional use of soil.

Moreover, the efficiency of the proposed method is significantly limited by the disregarded consistency of the relationship between the soil and the phytostabilizing plant, since the key focus is only on the process of phytostabilization, which is aimed at reproducing the biocenosis, while the specific properties of the soil are not considered. However, the remediation potential of plants in terms of the level of heavy metal contamination can be significantly increased by applying supplementary measures aimed at raising the geochemical barrier at the soil-root boundary and by activating internal defence mechanisms of the plant itself. Thus, the integrated use of various though unidirectional measures of heavy metals stabilization in soil and reducing their toxic effects on plants balances the abovementioned limitations. The sesquioxides, pedogenic phosphates, calcium carbonates, humic substance, and pH values produce a significant effect on the availability of

heavy metal compounds in soils, and therefore their availability to plants. It should be noted that the use of phytostabilization alone does not always provide the desired ecological effect of toxicity abatement and restoring ecological functions of polluted soils of urban ecosystems; therefore, it is appropriate to combine it with chemical detoxification through the application of various ameliorants to increase their buffering capacity.

That is why the issue of creating a methodological approach and specific technologies based on it is most relevant for phytostabilization of urban soils, taking into account the peculiarities of urban ecosystems with a high level of man-made impact to ensure environmental safety of the areas of man-induced load.

Methods

The development of a new methodological approach to ensure phytostabilization of urban ecosystem soils contaminated with metal compounds provided for the following conditions: increasing the phytoremediation potential of the stabilizing plant by using a rooting compound, through the creation of a branched root system, to smooth the signs of degradation of urban soils by applying the microbiological preparation, and to reduce the availability of the heavy metal compounds by introducing the ameliorant (Table 2).

Table 2. Substantiation of phytostabilization components of urban ecosystem soils contaminated with heavy metals

Requirements to the plant	Presence of the soil degradation	Additional preparation for plant development	Additional conditions for decreasing the migration capacity of metals
BAC < 0.25 and TC < 0.25 uncontaminated soil BAC < 1.00 and TC < 1.00 contaminated soil	microbiological preparation	rooting compound	ameliorant

BAC – biological absorption coefficient, TC – tissue coefficient

The suggested approach was tested in the conditions of high levels of lead contamination of the urban ecosystem soils in the city of Dnipro (Ukraine) to observe the expected environmental effect.

The versions of the experiment on soil phytostabilization are as follows:

- 1 – control (uncontaminated soil);
- 2 – contaminated soil at a Pb dose of 429.67 mg/kg – 14.3 maximum permissible concentration (MPC) + alfalfa (*Medicago sativa*) (phytostabilizer);
- 3 – contaminated soil at a Pb dose of 14.3 MPC + alfalfa (*Medicago sativa*) (phytostabilizer) + K₂CO₃ (ameliorant);

4 – contaminated soil at a Pb dose of 14.3 MPC + alfalfa (*Medicago sativa*) (phytostabilizer) + K_2CO_3 (ameliorant) + Stymovit Ferti (rooting compound);

5 – contaminated soil at a Pb dose of 14.3 MPC + alfalfa (*Medicago sativa*) (phytostabilizer) + K_2CO_3 (ameliorant) + Stymovit Ferti (rooting compound) + BTU-r multipurpose biocomplex (microbiological preparation).

The zonal soil of the Northern Steppe of Ukraine was chosen as a reference, i.e., ordinary low-humus heavy loam black soil formed in the forest under the forb-fescue-feather grass plant association in the conditions of non-leaching regime. The total lead content in uncontaminated soil was 22.4 mg/kg, available forms (extract of AAB, pH 4.8) – 0.10 mg/kg.

Contaminated soil was represented by urban fill soil, which was formed on the top of zonal soil of ordinary low-humus heavy loam black soil with a total lead content of 363.83 mg/kg and available forms of 73.52 mg/kg.

K_2CO_3 was introduced in the form of an aqueous solution prior to sowing seeds, followed by digging-in and thorough mixing of soil. The ameliorant dose was 1.5 times greater than the equivalent amount required for complete chemical binding of a heavy metal cation, which under conditions of 14.3 MPC for Pb corresponded to 397.24 mg K_2CO_3 per 1 kg of contaminated soil.

Stymovit Ferti (rooting compound) is a highly effective organic fertilizer made from biohumus, enriched with macro- and micronutrients, as well as a complex of biologically active substances of natural origin, containing the following: humic substances – up to 1.5%, N – 1.0%, P – 1.8%, K – 1.3%, Mn – 50.0 mg/L, Mg – 0.2 mg/L, Zn – 25.0 mg/L, Cu – 50.0 mg/L, Co – 5.0 mg/L. Due to the high content of humic substances and phosphates, its action is aimed at fixing lead cations as poorly soluble compounds inaccessible to the root system of plants. Prior to planting, the seeds were inoculated in the ratio of 1 part of the preparation to 10 parts of water during 1 day. During the vegetation period, soil dressing was carried out at the rate of 1 part of the preparation to 40 parts of water every two weeks according to the proposed recommendations for the Stymovit Ferti (rooting compound) application.

BTU-r multipurpose biocomplex microbiological preparation contains nitrogen-fixing, fungicidal, phosphorus- and potassium-mobilizing broad spectrum bacteria. The experiment used its action, aimed at increasing the

mobility of phosphates, which, in turn, would be able to precipitate metal cations in the soil solution. The soil dressing in the ratio of 3 mL to 1 L of water was carried out according to the proposed recommendations for use every two weeks, alternating with the application of Stymovit Ferti (rooting compound).

Alfalfa (*Medicago sativa*) was selected as the test plant, a flowering perennial plant of legume family (*Fabaceae*), which like all legumes fixes molecular nitrogen from the atmosphere owing to the nodule bacteria, so with a long-continued cultivation it can increase soil fertility and due to its decorative properties will fit in green areas of the city.

The lead content was defined by the atomic absorption analysis in plants after wet ashing, in the soil after acid treatment.

The efficiency of the suggested phytostabilization technique, which was carried out using the phytoremediation potential of the plants under study, was defined using the BAC (1) and TC (2):

$$BAC = \frac{C_{p_i}}{C_{s_i}} \quad (1)$$

$$TC = \frac{C_{aer.p_i}}{C_{f.end_i}} \quad (2)$$

Where: C_{p_i} – the content of metal cations in the plant or in its part, mg/kg; C_{s_i} – the content of metal cations in the soil after acid treatment, mg/kg; $C_{aer.p_i}$ – the content of metal cations in the aerial part of a plant, mg/kg; $C_{f.end_i}$ – the content of metal cations in the underground part of a plant, mg/kg.

The phytostabilization technology was considered successful with the values of TC and $BAC < 1$ (Fitz and Wenzel, 2002).

Results and Discussion

Substantiation of components of phytostabilization of lead-contaminated urban ecosystem soils Alfalfa (*Medicago sativa*)

Alfalfa (*Medicago sativa*) was not chosen accidentally, and it was due not only to its low BAC and TC values

relative to lead, but also to its ability to fix molecular nitrogen with nodule bacteria, ensuring the involvement of this macronutrient in urban soil with poor mineral nutrition for plants.

The processes of nitrogen accumulation in the nodules proceed as follows: from the beginning of the nodules' formation on the roots, which is the period from the first leaves coming out to full flowering, the nitrogen supply in the nodules increases, followed by a dramatic decrease after flowering. The flowering phase of legumes is a turning point in the activity of nodule bacteria. The nature of physiological and biochemical processes taking place in the legume before flowering and after it is quite different, namely: bacteria that have settled in the root parenchyma of legumes fix molecular nitrogen from the air and convert it into protein substances, but after some time, influenced by the plant, the bacteria switch to a bacteroid form, and from this moment, the nitrogen fixation drops sharply and discontinues. Therefore, the active period of nodule bacteria in terms of air nitrogen fixation is limited to 180–200 days in forage grasses, including alfalfa (*Medicago sativa*). Unfortunately, the factors that cause increased nitrogen fixation by nodule bacteria are still insufficiently studied. The possible internal causes that inhibit the activity of legumes and nodule bacteria in their root system are also unknown. However, during the vegetation period under normal temperature and precipitation conditions of the Northern Steppe of Ukraine, they can introduce up to 180–200 kg of nitrogen on an area of 1 ha (the content in the root system and aerial biomass).

K₂CO₃ ameliorant

Absorbing ameliorants allow reducing the removal of lead from soil by phytostabilizing plants by binding its cations capable of migration (extract of AAB with pH 4.8) as compounds inaccessible to the root system of plants. When choosing the ameliorant, the focus was primarily on the reliability of mitigation of the toxic effects of environmentally hazardous lead compounds, and secondly, on the relative cheapness and availability of raw materials. It is known that CaCO₃ acts as the geochemical barrier to the migration of heavy metals in soil profile, being one of the components of the mechanism of buffering capacity to distribute contamination in soil (Il'in, 1995). Ordinary low-humus heavy loam black soil

in native conditions contains up to 0.5% of carbonates, concentrated mostly in the root layer. Carbonates greatly reduce the availability of heavy metals in soil, which is based, firstly, on the absorbing properties of highly dispersed fractions of carbonates, and secondly, is conditioned by the indirect effect through the regulation of the soil environment reaction. The reaction of the soil environment is interrelated with the redox potential, their combination conditions the migration capacity of heavy metals. High values of redox potential reduce the activity of electrons in soil, the density of the electron cloud and the charge of acidoids. Growing redox potential produces an impact on the soil selective absorption of cations with a lower charge density. High values of redox potential and alkaline reaction of the soil environment initiate lead deposition in the form of oxides and hydroxides poorly soluble in water. At aerogenic input, due to CaCO₃ available in buffering soils, there is no migration of heavy metals, so there is no risk of secondary contamination of groundwater. Hence the idea of using carbonates to detoxify soils of urban ecosystems with a man-caused impact, contaminated with heavy metals; however, it seems appropriate to replace the Ca²⁺ cation with K²⁺ – a vital macronutrient necessary for plants throughout the vegetation period. Potassium plays an important role in the plants' ability to tolerate stress, which can be caused by external factors such as drought, frost, heavy rates of light and attacks of pests and diseases. This macronutrient is important for many functions of a plant, such as enzyme activation, protein synthesis, photosynthesis, etc. The lead carbonate formed as a result of the reaction is a slightly soluble compound (yield of solubility $1.1 \cdot 10^{-5}$ g per 100 g of soil solution), however, like all other metal carbonates.

Stymovit Ferti rooting compound

Considering the components conditioning the mechanism of soil buffering in terms of lead contamination (content of humus, phosphates, carbonates, R₂O₃, pH), it is appropriate to intensify the effect of ameliorant by applying organic matter. Stymovit Ferti rooting compound is a highly effective organic fertilizer. It is made of biohumus, enriched with macro- and microelements, as well as a complex of biologically active substances of natural origin. The high content of phosphates results in the deposition of heavy metal cations from the

soil solution, as heavy metal phosphates are insoluble and slightly soluble compounds, for example, the yield of solubility for $Pb_3(PO_4)_2$ is $1.4 \cdot 10^{-5}$ g per 100 g of soil solution. The humic substances will promote the formation of organo-mineral complexes with lead cations. When bioactive substances of natural origin get into the alfalfa plants (*Medicago sativa*), they stimulate their growth and development, boost immunity, and intensify metabolic processes aimed at detoxification of metabolic products induced by lead, which is essential for weakened plants with an imbalance of mineral nutrients at a man-caused impact on anthropogenically disturbed soils of urban ecosystems.

BTU-r multipurpose biocomplex microbiological preparation

Soil microorganisms are an integral part of circulation of all nutrients necessary for adequate plant nutrition; moreover, they are directly involved in soil formation, and improve the ecological properties of the soil. This is very important for urban ecosystems. Due to the soil microorganisms and enzymes involved in the process, the synthesis and decomposition of organic matter is carried out along with the transformation of man-made pollutants, etc. The ecological consequences of lead contamination are evident as a decrease in the total number and species diversity of microorganisms, increasing the absolute dominance of a small number of species, mostly fungi, usually not typical of normal conditions, with phytotoxic properties. *Streptomyces actinomycetes* (Zvyaginets, 1986), *Rhodotorula rubra* epiphytic yeast, *Azotobacter chroococcum*, and *Chlorella vulgaris* algae (Andreyuk et al., 2001) have been found to be the most sensitive to the toxic effects of environmentally hazardous metal compounds. However, from the point of view of restoring the ecological functions of the soil, their influence on the groups of microorganisms responsible for the transformation of nutrients (N, P, K) is of much interest. After all, when soil is contaminated with heavy metals and their ability to migrate increases (content in the extract of AAB with pH 4.8), a general trend of declining numbers of phosphorus-mobilizing, acid-forming bacteria and those taking up mineral nitrogen is discovered, and on the contrary, the number of bacteria related to the transformation of nitrogen from organic compounds as well as microscopic fungi increases. These processes result in mineral nutrition imbalance of plants,

especially in anthropogenically disturbed soils of urban ecosystems. Therefore, to create a positive balance of soil formation and accelerate the accumulation of nutrients in conditions of human-induced pressure, it is necessary to intensify the activity of soil microorganisms.

The BTU-r multipurpose biocomplex contains, along with nitrogen-fixing, fungicidal and potassium-mobilizing bacteria, the phosphorus-mobilizing bacteria, the action of which is aimed at maintaining the proper level of phosphates in the soil, which in turn provides additional binding of lead cations with soil-forming phosphates. Thus, the microbiological preparation produces effect on urban soils in two areas of focus: first, the restoration of their ecological functions by accelerating the transformation processes in compounds containing nutrients, and secondly, eliminating toxicity by reducing the content of available forms of lead.

Efficiency of phytostabilization of urban ecosystem soils contaminated with lead based on an integrated approach

With the development of the set of measures, Pb^{2+} intake by the plant was blocked. According to the BAC and TC values, both external protective mechanisms, which are primarily a reaction of the soil environment, and internal ones, directly inherent in the plant, worked out (Table 3). The proposed approach was not limited to a purely chemical process of binding of Pb^{2+} cations, but activated a number of protective mechanisms in the "soil – plant" system, which is very important for anthropogenically disturbed soils of the urban ecosystem, characterized by poor biological activity and nutrient transformation, and therefore scarce environmental properties. Thus, the BAC value in this variant was the lowest as compared with the contaminated option and approached the reference figures. The acropetal distribution of lead in the organs of the alfalfa plant (*Medicago sativa*) was clearly defined in terms of TC. It should be noted that the combined application of the ameliorant, K_2CO_3 , Stymovit Ferti rooting compound and the BTU-r multipurpose biocomplex caused the largest decrease in available forms of lead – up to 10.4% of their total content in contaminated soil among the studied options. With the least removal of Pb^{2+} by alfalfa plants (*Medicago sativa*) according to the BAC and TC values, this confirmed the reliability of their fixing by carbonates and organo-mineral complex, and therefore substantiated the prospects of using the suggested approach.

Table 3. Phytoremediation potential of alfalfa (*Medicago sativa*)

Variant	BAC		TC
	Aerial part of plants	Roots	
Control (uncontaminated soil)	0.08	0.12	0.67
Contaminated soil at a Pb dose of 14.3 MPC + alfalfa (<i>Medicago sativa</i>) (phytostabilizer)	0.39	0.44	0.87
Contaminated soil at a Pb dose of 14.3 MPC + alfalfa (<i>Medicago sativa</i>) (phytostabilizer) + K ₂ CO ₃ (ameliorant)	0.27	0.37	0.73
Contaminated soil at a Pb dose of 14.3 MPC + alfalfa (<i>Medicago sativa</i>) (phytostabilizer) + K ₂ CO ₃ (ameliorant) + Stymovit Ferti (rooting compound)	0.23	0.34	0.68
Contaminated soil at a Pb dose of 14.3 MPC + alfalfa (<i>Medicago sativa</i>) (phytostabilizer) + K ₂ CO ₃ (ameliorant) + Stymovit Ferti (rooting compound) + BTU-r multipurpose biocomplex (microbiological preparation)	0.19	0.31	0.62

Development of a mechanism to create phytostabilization technologies based on an integrated approach

The research evidence is the basis for the development of a mechanism to create the techniques for the soil phytostabilization in urban ecosystems on the basis of a comprehensive approach to the unidirectional measures to ensure the maximum possible effect of eliminating toxicity caused by heavy metal pollution.

The pattern of creating the technologies of phytostabilization of soil contaminated with heavy metals is provided in Fig. 1. The first stage involves a detailed study of conditions of pollution of the urban ecosystem under man-induced impact, which should take into account the first-time soil pollution, particularly, the heavy metals causing it, their total content, ability to migrate, and secondly, the state of disturbed urban soil, such as the content of nutrients, microbiological activity, vegetation availability, etc.

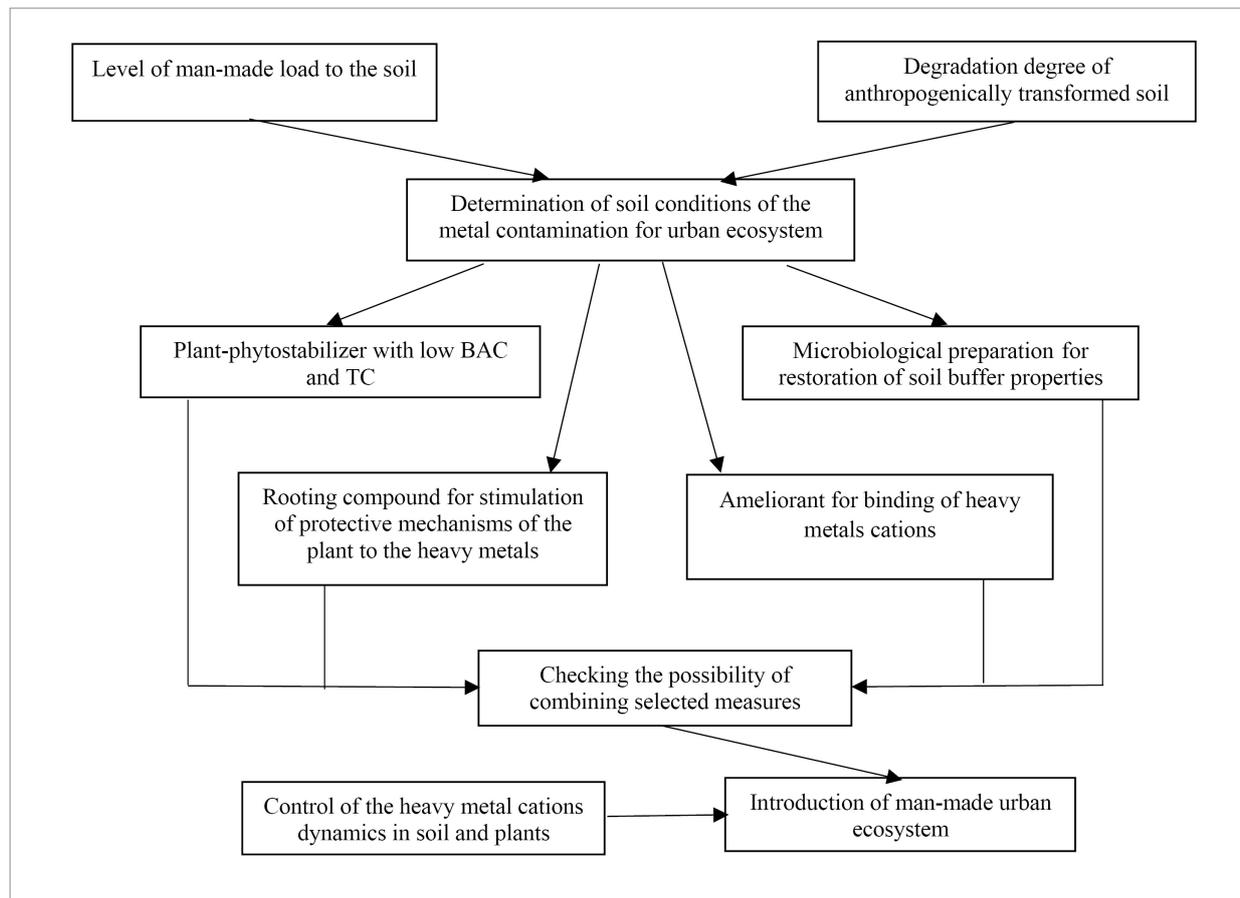
The second stage includes selecting a phytostabilizing plant on the basis of the detailed analysis of the received information, as well as choosing a stimulator of internal defence mechanisms of a plant, an ameliorant for metal cations fixing in soil, a microbiological preparation to restore the protective functions of soil. The availability of a significant amount of information on the phytostabilizing effect of vegetation allows defining the most effective one for a particular metal pollutant, as well as soil and climatic

conditions. An additional evidence confirming the correct choice of a phytostabilizer is the availability of the selected plant species in the phytocenosis of the urban ecosystem. Preference will be given to the plants with a branched root system to increase the metals yield from contaminated soil. It is advisable to increase the root system by applying a rooting compound, which, in turn, is selected for a particular species of phytostabilizing plants. A detailed analysis of soil pollution in the urban ecosystem will allow selecting the ameliorant. Organic substances, chelates, ion exchange resins, brown coal, lime, plaster stone, chalk, zeolite, vermiculite, clay pellets, red mud, calcined bentonite, potassium carbonate and potassium sulphide, mineral phosphorus-containing and organic (sapropel, peat, manure, chicken manure, biohumus) fertilizers are currently used as ameliorants to reduce the availability of heavy metals. It should be noted that the dose of ameliorant should correspond to the degree of heavy metal contamination of soil in the urban ecosystem. Degraded soils of urban ecosystems are usually characterized by lower content of nutrients available to the root system of plants as compared to zonal soils, on which they were formed as a result of human-induced activities, which, in turn, hinders the growth and development of phytostabilizing plants. Therefore, the involvement of microbiological preparations, which contain, first of all, phosphorus-mobilizing bacteria, will promote, firstly, their transformation into more accessible forms for the root system, which

serves as an additional nutrition source for phytostabilizers, and, secondly, reduce the content of available forms of heavy metals due to phosphate deposition. The

microbiological preparation should be selected based on the phytostabilizer requirements for the soil and considering the degree of degradation.

Fig. 1. Stages of phytostabilization



At the third stage, the possibility of combining the selected measures is tested in a laboratory environment during cultivation experiments, and the most effective combination is singled out based on BAC and TC of the phytostabilizing plant. It is desirable to include the intermediate options in an experiment to determine the efficiency of each of the selected components.

The fourth stage involves testing of the developed technique of phytostabilization of urban ecosystem soil contaminated due to human-induced activity in a production environment, which should take place under strict control over the content and availability of heavy metals

in the soil and their accumulation in the foot end and aerial parts of plants.

Conclusion

It has been proved that the existing techniques for phytostabilization of heavy metal contaminated soils of urban ecosystems are limited to a certain degree in terms of implementation efficiency. A new approach to the combined use of phytostabilization and chemical detoxification methods has been proposed, taking into account the

current state and all factors producing effect on the urban ecosystem and based on specific conditions. A mechanism for creating phytostabilization techniques has been developed driven by a comprehensive approach using unidirectional measures to achieve the maximum possible effect of reducing toxicity by involving stimulants of internal defence mechanisms of a plant, ameliorants for binding heavy metal cations in soil and microbiological preparations to restore its protective functions. The most effective combination of components of the integrated phytostabilization technique has a sustainable ecological effect, reducing the migration ability of heavy metals in

the soil and their translocation in plants. To partially solve the problem with a high content of metal cations in urban soils and the risk of spreading pollution to adjacent environments, the feasibility of phytostabilization through the use of alfalfa (*Medicago sativa*) in combination with detoxification with an aqueous solution of potassium carbonate and the application of the BTU-r multipurpose biocomplex microbiological preparation has been experimentally confirmed. Such a combination provides, according to the BAC and TC values, the lowest yield of Pb^{2+} by plants as well as a significant reduction in its migration ability in the soil.

References

- Andreyuk K.I., Iutinska G.O., Antipchuk A.F., Koziric'ka V.C., Ponomarenko S.P. (2001). Funkcionuvannya mikrobnih cenoziv r'runtu v umovah antropogennogo navantazhennya. Kiiiv. Naukova dumka. [Functioning of soil microbial coenoses in the conditions of anthropogenic loading] 240 p.s. (in Ukrainian).
- Cetinkaya G., Sozen N. (2011). Plant species potentially useful in the phytostabilization process for the abandoned CMC mining site in Northern Cyprus. *International Journal of Phytoremediation* 13(7): 681-691. Available at: <https://doi.org/10.1080/15226514.2010.500155> (accessed 12 April 2021).
- Conesa H.M., Faz A, Arnaldos R. (2006). Heavy metal accumulation and tolerance in plants from mine tailings of the semi-arid Cartagena-La Union mining district (SE Spain). *Science of the Total Environment* 366: 1-11. Available at: <https://doi.org/10.1016/j.scitotenv.2005.12.008> (accessed 12 April 2021).
- EPA. (1997). Recent developments for in situ treatment of metal contaminated soils, U.S. Environmental Protection Agency, Washington.
- Erakhrumen A., Agbontalor A. (2007). Review phytoremediation: an environmentally sound technology for pollution prevention, control and remediation in developing countries. *Educational Research and Review*. Vol. 2, No. 7, July. pp. 151-156. Available at: https://academicjournals.org/article/article1379597261_Erakhkrumen.pdf (accessed 12 April 2021).
- Erdei L., Mezosi G., Mecs I., Vass I., Foglein F., Bulik L. (2005). Phytoremediation as a program for decontamination of heavy-metal polluted environment. In: *Proceedings of the 8th Hungarian Congress on Plant Physiology and the 6th Hungarian Conference on Photosynthesis, Acta Biologica Szegedien-sis, Hungary, Vol. 49, No. 1-2, pp. 75-76*. Available at: www2.sci.u-szeged.hu/ABS/2005/Acta%20HP/4975.pdf (accessed 12 April 2021).
- Fagnano M., Visconti D., Fiorentino N. (2020). Agronomic approaches for characterization, remediation, and monitoring of contaminated sites. *Agronomy* 10 (9) 1335: 14 pages. Available at: <https://doi.org/10.3390/agronomy10091335> (accessed 12 April 2021).
- Fitz W.J., Wenzel W.W. (2002). Arsenic transformation in the soil - rhizosphere - plant system, fundamentals and potential application of phytoremediation. *Journal of Biotechnology*. 13;99(3): 259-278. Available at: [https://doi.org/10.1016/S0168-1656\(02\)00218-3](https://doi.org/10.1016/S0168-1656(02)00218-3) (accessed 12 April 2021).
- Gonzalez R.C, Gonzalez-Chavez M.C.A. (2006). Metal accumulation in wild plants surrounding mining wastes. *Environmental Pollution*. 144: 84-92. Available at: <https://pubmed.ncbi.nlm.nih.gov/16631286> (accessed 12 April 2021). <https://doi.org/10.1016/j.envpol.2006.01.006>
- Il'in V.B. (1995). Ocenka bufernosti pochv po otnosheniyu k tyazhelym metallam. [Assessment of the soil buffering capacity in relation to heavy metals]. *Agrohimiya*. 10: 109-113. (in Russian).
- Irtelli B., Nicolazzi S.A., Quartacci M.F., Navari-Izzo F. (2006). Phytoremediation of heavy metals from a real contaminated soil by *B. carinata*: effect of highly biodegradable chelators and succession with wild species. In: *Abstract book of the 1st Scientific Meeting of WG1: Root to Shoot Translocation of Pollutants and Nutrients, Santiago de Compostela, 22-24 June 2006, P. 40*. Available at: <http://w3.gre.ac.uk/cost859/WG1/WG1-Santiago-2006Abstracts.pdf> (accessed 12 April 2021).
- Mendez M.O, Maier R.M. (2008). Phytostabilization of mine tailings in arid and semiarid environments - an emerg-

ing remediation technology. *Environmental Health Perspective*. 116(3): 278-283. Available at: <https://ehp.niehs.nih.gov/doi/10.1289/ehp.10608> (accessed 12 April 2021). <https://doi.org/10.1289/ehp.10608>

Rosario K., Iverson S. L., Henderson D.A., Chartrand S., McKeon C., Glenn E.P. (2007). Bacterial community changes during plant establishment at the San Pedro River mine tailings site. *Journal of Environmental Quality*. 36: 1249-1259. <https://access.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2006.0315> (accessed 12 April 2021). <https://doi.org/10.2134/jeq2006.0315>

Salas-Luevano M.A., Manzanares-Acuna E., Letechipia-de Leon C., Vega-Carrillo H.R. (2009). Tolerant and hyperaccumulators autochthonous plant species from mine tailing disposal sites. *Asian Journal of Experimental Sciences*. 23(1): 27-32. Available at: <https://www.cabdirect.org/cabdirect/abstract/20093054229> (accessed 12 April 2021).

Tang C., Chen Y., Zhang Q., Li J., Zhang F., Liu Z. (2019). Effects of peat on plant growth and lead and zinc phytostabilization from lead-zinc mine tailing in southern China: Screening plant species resisting and accumulating metals. 176: 42-49. <https://www.sciencedirect.com/science/article/abs/pii/S0147651319303501?via%3Dihub> (accessed 12 April 2021). <https://doi.org/10.1016/j.ecoenv.2019.03.078>

Tangahu B.V., Abdullah S.R.S., Basri H., Idris M., Anuar N., Mukhlisin M. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering*. Article ID 939161: 31 pages. <https://doi.org/10.1155/2011/939161> (accessed 12 April 2021).

Vangronsveld, J., Cunningham, S. (1998). Metal-contaminated soils: In situ inactivation and phytoremediation. Georgetown, TX: Springer-Verlag and R.G. Landes Company.

Yakovyshyna T.F. (2011). Fitostabilizaciya pochvy, zagryaznenoj tyzhelymi metallami [Phytostabilization of soil, contaminated by the heavy metals]. In: Proceedings of the II International scientific and practical conference: Innovaciï ta transfer tekhnologij: vid ideï do pributku, Dnipropetrovs'k, 26-27 April 2011, pp. 33-34. (in Ukrainian).

Yakovyshyna T.F. (2014). Fitoremediacionnaya sposobnost' sel'skohozyajstvennyh kul'tur k zagryazneniyu pochvy tyzhelymi metallami. [Phytoremediation ability of agricultural crops to soil contamination with heavy metals] *Estestvennye i matematicheskie nauki v sovremennom mire*. 22: 44-48. (in Russian).

Zvyagincev D.G. (1986). *Ekologicheskaya rol' mikrobyh metabolitov*. Moskva, MGU. [Ecological role of microbial metabolites]. 240 p.s. (in Russian).

