BULLETIN OF NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN
ISSN 1991-3494
Volume 5, Number 387 (2020), 34 – 40 **https://doi.org/10.32014/2020.2518-1467.140**

UDC 502.132: 631.453
IRSTI 87.21.03

B. K. Yelikbayev[1], Marcela C. Pagano[2], G. A. Jamalova[1]

[1]Satbaev University, Almaty, Kazakhstan;
[2]Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil.
E-mail: bek29k@gmail.com, marpagano@gmail.com, j.ga@bk.ru

HYPERACCUMULATOR PLANTS FOR PHYTOREMEDIATION OF SOIL CONTAMINATED WITH HEAVY METALS

Abstract. Environmental pollution, including pollution of urban soils by heavy metals causes serious environmental concern around the world. Heavy metals accumulate relatively quickly in soil but their removal rate is very slow. Hyperaccumulator plants help cleanse the environment from heavy metals. Phytoremediation is cleansing of soils contaminated with heavy metals, using plants that accumulate significant amounts of metals. An important environmental problem in large industrial cities is pollution by toxic compounds, including heavy metals. Due to the potential toxicity and high resistance of metals, soils contaminated with these elements are an environmental problem that requires effective and affordable solution. In soils heavy metals are in varying degrees of accessibility to plants. Water-soluble forms of heavy metals, as a rule, are presented in the form of various salts and organic complex compounds. Phytoremediation of urban soils from heavy metals is an important environmental challenge. Among the wild species, a special group of heavy metal hyperaccumulator plants is highlighted. Some of the land plants that can accumulate abnormally high levels of potentially toxic trace elements are known as “hyperaccumulators” and their number includes about 500 taxa. Phytoremediation is much more environmentally friendly and cheaper than other techniques, so recently it has received widespread use in various countries.

Key words: Phytoremediation, heavy metals, hyperaccumulators, phytoextraction, urban soils.

Introduction. Recently, there has been an increased interest in study of ecological state of environmental object located in urban areas. Study of soil and soil cover takes an important place in such research. Urban soils are poorly studied biological systems that differ in some properties from natural ones. They are characterized by high mosaic and irregularity of profile, significant compaction, alkaline reaction, pollution with various toxic substances. Thus, an important environmental problem in large industrial cities is pollution by toxic compounds, including heavy metals [1-3]. In soils, heavy metals are in varying degrees of accessibility to plants. Water-soluble forms of heavy metals, as a rule, are represented by chlorides, nitrates, sulfates and organic complex compounds. Heavy metals accumulate relatively quickly in soil and are very slowly removed from it: the half-removal period of zinc is up to 500 years, cadmium - up to 1100 years, copper - up to 1500 years, lead - up to several thousand years [4]. Heavy metals are highly toxic substances due to their high lethality; they are not biodegradable and have low mobilization ability in the environment. Therefore, they cause soil and water pollution, as well as toxic, genotoxic, teratogenic and mutagenic effects in living organisms, causing endocrine and neurological disorders even at low concentrations [5-7].

Regarding phytoremediation technology. Restoring the environment with plants is of great interest around the world due to the possibilities that phytoremediation technology opens up for cleansing upper layers of contaminated soils [4,15]. Phytoremediation is the most suitable alternative to traditional technologies of physical and chemical rehabilitation, which are very expensive and technically more suitable for small areas, create secondary pollution and impair soil fertility. Phytoremediation method does not require large expenditures, it is simple in practical implementation, and is applicable in any environmentally unfavorable zones [10-13].

The effect of nickel hyperaccumulation by plants was first noted in the seventies of the twentieth century [8.9]. Since then, study of hyperaccumulators has attracted attention of plant physiologists, molecular biologists and biotechnologists. Advances in study of hyperaccumulators have led to identification of about 500 taxa capable to hyperaccumulate various elements [14]. Some of the land plants that can accumulate abnormally high levels of potentially toxic trace elements are known as "hyperaccumulators" [15]. These plants have been the subject of intensive research in recent decades, which has led to their widespread use in biotechnologies for soil cleaning [16], phytoproduction [17] and nanotechnology [18,19].

Studies show that plants can cleanse the environment from metals, and phytoremediation allows use of green plants for removing pollutants from surface layer of soils or turn the latter into harmless compounds, making it a promising method. Among wild-growing species, a special group of heavy metal hyperaccumulator plants is distinguished. Their shoots are able to accumulate from 1,000 to 30,000 mg of metal per kilogram of dry mass of plant without visible signs of damage [20,14]. Cultivation of heavy metal hyperaccumulator plants in contaminated areas allows to cleanse soil of excess metals [21-23].

Hyperaccumulation of heavy metals in soil. The first threshold values for hyperaccumulation of trace elements were determined as follows: 1000 mg / kg for Ni, Co, Cu, Cr, Pb and > 10000 mg / kg for Zn and Mn [20, 24]. According to Yang et al. [25], the threshold value for Zn should be reduced to 3000 mg / kg. Sun et al. [26] suggested that the threshold for Cd should be 100 mg / kg. A new updated and revised proposal for thresholds considers a plant a candidate for hyperaccumulator if its dry matter of aboveground tissue contains more than 100 mg / kg Se, Cd and Tl, 300 mg / kg Cu, Co, Cr, 1000 mg / kg Ni and Pb, 3000 mg / kg Zn and 10000 mg / kg Mn [14]. In addition, Pratas et al. [27 suggested a threshold level of 1 mg / kg for Ag.

Critical evaluations of hyperaccumulation reports mentioned that hyperaccumulative plants are now broadly divided into eight groups: (i) plants from ultrabasic soils showing hyperaccumulation of Ni (and rarely Co); (ii) plants from soils enriched with chalcophilic elements, such as Zn, Pb, Cd and Tl, which may exhibit hyperaccumulation of any of these elements; (iii) plants from soils rich in Cu and Co, exhibiting hyperaccumulation of one or both of these elements; (iv) plants exhibiting hyperaccumulation of Mn, which may arise from some ultrabasic soils and from some other substrates; (v) plants with unusually high concentration of Se from soils with increased concentrations of this element; (vi) plants that have been identified as hyperaccumulators based on the absorption of elements from industrially contaminated soils, which include many of the elements listed above, as well as reports of hyperaccumulation of Cr and As; (vii) plants reported to accumulate light rare earth elements such as Ce and La; and (viii) plants reported to be hyperaccumulating basic soil elements (that is, those that are higher than concentration of microelements), such as Fe or Al, a category that we will not discuss further [14,28,29,12,30].

Since the decorative flower crops used to create flower beds are practically not considered as means of soil remediation, but rather for decorative purposes and so far haven't been taken much into account, studying their accumulating abilities is also very important [31].

Due to the potential toxicity and high durability of metals, soils contaminated with these elements are an environmental problem that requires an effective and affordable solution. Phytoextraction has been developed as part of intensive research for more efficient, cheaper and less hazardous methods to remove contaminated soils. It is based on removal of metals by plants through absorption and accumulation in biomass [32].

Hyperaccumulative plants. Hyperaccumulators have found their widest application in phytoextraction, which is one of the phytoremediation strategies [33,24,35]. The ideal plant kinds to be used in this process should have: (i) high biomass production, rapid growth and easy assembly (the short time needed to effectively reduce the concentration of elements in phytoremedic soils, [36-38] (ii) the ability to exist outside its native region [33,39,40]. The second feature is often problematic because hyperaccumulators are often endemic and their appearance is limited to contaminated sites. It is estimated that almost 90% of known hyperaccumulators are endemic for metal-containing soils, such as serpentine soil [41].

Along with hyperaccumulative herbaceous plants, several species of tree species are considered promising for further study. Since many woody plants grow quickly, have deep roots, produce abundant biomass, and several species show some ability to tolerate and accumulate heavy metals. In recent years, significant progress has been made in identifying native plants and developing genetically modified woody plants to restore the environment contaminated with heavy metals. On a large scale, metal uptake by trees can be more efficient, mainly because of a deeper root system and higher biomass yields [42,43].

Phytoremediation is based on removal of contaminants from soil by using mechanisms such as phytoextraction, phytodegradation, rhizofiltration, phytostabilization and phytovolysis [44,45,6,12], but the mechanisms involved in heavy metals regeneration are limited by absorption, adsorption, transport and translocation, sequestration in vacuoles, supersaturation and, in some cases, volatilization [46].

Two main areas of interest for the study of new hyperaccumulators include: (i) identification of new indigenous plant species that demonstrate tremendous ability to bind elements [47,48] and (ii) search for multi-element hyperaccumulators called coaccumulators [49] that can be used during phytoremediation of contaminated soils.

Use of synthetic chelators and mineral fertilizers effectively stimulates accumulation of heavy metals in plant organs by increasing bioavailability and productivity [50-55,45]. The addition of certain PGPR - bacterial strains and mycorrhizal fungi to plants rhizosphere also stimulates accumulation of heavy metals in plant organs [56-59].

One of the promising areas of phytoremediation of soils contaminated with heavy metals is usage of transgenic plants specially designed as hyperaccumulators [51,55,11,6].

Phytoremediation methods are developed and implemented in Bulgaria, the USA, Great Britain, Spain, Canada, China, Mexico, New Zealand and other countries [15,16]. However, implementation of this environmental protection technology in the CIS countries is largely hindered by the need to search for heavy metal accumulator plants adaptable to our environmental conditions or use of introducers. Nevertheless, the work of researchers from Kazakhstan and the CIS on accumulation of heavy metals by wild-growing and cultivated plants provides sufficient grounds for finding plants suitable for introducing phytoremediation technology in Kazakhstan and the CIS [55,60-66]. In Kazakhstan, scientists from the Institute of Biology and Biotechnology of the MES RK and other organizations are actively involved in improving phytoremediation methods [55,63,64].

Conclusion. Heavy metals are highly toxic substances, they are not biodegradable and have low mobilization ability in the environment. Therefore, restoration of the environment through plants is of great interest throughout the world, which opens possibilities for phytoremediation technology for cleaning the upper layers of contaminated soils. The phytoremediation method does not require large expenditures, is simple in practical implementation, and is applicable in any environmentally unfavorable zones. Advances in study of hyperaccumulators have led to the identification of about 500 taxa capable of hyperaccumulation of various elements. The phytoremediation method does not require large expenditures, is simple in practical implementation and is applicable in any environmentally unfavorable zones. Almost 90% of known hyperaccumulators are endemic. The use of synthetic chelators and mineral fertilizers effectively stimulates accumulation of heavy metals in plant organs by increasing bioavailability and productivity. Among promising areas of phytoremediation of soils contaminated with heavy metals is use of transgenic plants specially designed as hyperaccumulators. Phytoremediation methods are developed and implemented in different countries of the world, including Kazakhstan.

Б. К. Еликбаев[1], Марсела К. Пагано[2], Г. А. Жамалова[1]

[1]Satbayev University, Алматы, Қазақстан;
[2]Минас-Жерайс федералды университеті, Бело Оризонте, Минас-Жерайс, Бразилия

АУЫР МЕТАЛДАРМЕН ЛАСТАНҒАН ТОПЫРАҚ ФИТОРЕМЕДИАЦИЯСЫНА АРНАЛҒАН ӨСІМДІК-ГИПЕРАКУМУЛЯТОРЛАР

Аннотация. Соңғы уақытта қала аумағындағы қоршаған орта объектілерінің экологиялық жай-күйін зерттеуге қызығушылық артып келеді. Қала топырағы – аз зерттелген биологиялық жүйе. Олар улы қосылыстар, оның ішінде ауыр металдармен ластанады деп сипатталады. Ауыр металдар топырақта тез жиналады және өте баяу, яғни бірнеше мың жылға дейін шығарылады.

Фиторемедиация физикалық-химиялық оңалтудың дәстүрлі технологияларына ең қолайлы балама және үлкен шығынды талап етпейді, іс жүзінде жүзеге асыру жеңіл және кез келген экологиялық қолайсыз аймақтарда қолдануға болады. Зерттеулер көрсеткендей, кейбір өсімдіктер қоршаған ортаны металдан тазарта алады. Ластанған жерлерде ауыр металл гипераккумуляторларын өсіру топырақты ауыр металдардан тазартуға мүмкіндік береді.

Өсімдік гипераккумуляторлар қазіргі уақытта ауыр металдардың шоғырлану қабілетіне байланысты сегіз топқа бөлінеді. Осы процесте қолданылатын өсімдік түрлері биомассаның жоғары өнімі, жылдам өсуі және жеңіл жиналуы, сондай-ақ өзінің жергілікті аймағынан тыс жерлерде өсетін қабілеті болуы тиіс. Өйткені ашылған гипераккумуляторлардың 90% құрамында металл бар топырақ үшін эндемикалық түрлер болып саналады.

Фиторемедиация фитоэкстракция, фитодеградация, ризофильтрация, фитостабилизация және фитоволизаттау сияқты тетік көмегімен топырақтан ластаушы заттарды шығаруға негізделген, бірақ ауыр металдарды регенерациялауға қатысатын механизмдер сіңіру, адсорбция, көлік және транлокация, вакуольдардағы секвестрация, аса қаныгу және кейбір жағдайда ұшып кету арқылы шектелген. Сондықтан жаңа гипераккумуляторларды табу өте маңызды.

Синтетикалық хелаторлар мен минералдық тыңайтқыштарды қолдану биожетімділігі мен өнімділігін арттыру есебінен өсімдік органдарында ауыр металдың шоғырлануын тиімді ынталандырады. Кейбір pgpr - бактериялық штаммдар мен микоризді саңырауқұлақтардың өсімдік ризосферасына қосылуы, сондай-ақ өсімдік органдарында ауыр металдардың шоғырлану жағдайын ынталандырады.

Ауыр металдармен ластанған топырақты фиторемедиациялаудың перспективалық бағыттарының біріне гипераккумулятор ретінде арнайы жобаланған трансгендік өсімдіктерді пайдалану жатады.

Гипераккумуляторларды зерттеудегі жетістіктер әртүрлі элементтерді гипераккумуляциялауға қабілетті 500-ге жуық таксон анықталған. Фиторемедитация әдістері әлемнің түрлі елінде, соның ішінде Қазақстанда әзірленіп, енгізілуде.

Түйін сөздер: фиторемедиация, ауыр металдар, гипераккумуляторлар, фитоэкстракция, қала топырағы.

Б. К. Еликбаев[1], Марсела К. Пагано[2], Г. А. Жамалова[1]

[1]Satbayev University, Алматы, Казахстан;
[2]Federal University of Minas Gerais, Бело Оризонте, Минас-Жерайс, Бразилия

РАСТЕНИЯ-ГИПЕРАККУМУЛЯТОРЫ ДЛЯ ФИТОРЕМЕДИАЦИИ ЗАГРЯЗНЕННЫХ ТЯЖЕЛЫМИ МЕТАЛЛАМИ ПОЧВ

Аннотация. В последнее время отмечается повышенный интерес к исследованию экологического состояния объектов окружающей среды городских территорий. Городские почвы – это малоизученные биологические системы, отличные по ряду свойств от природных. Они характеризуются загрязненными токсичными соединениями, в том числе тяжелыми металлами. Тяжелые металлы сравнительно быстро накапливаются в почве и крайне медленно из нее выводятся до периода в несколько тысяч лет.

Фиторемедиация – наиболее подходящая альтернатива традиционным технологиям физико-химической реабилитации и не требует больших затрат, проста в практическом осуществлении и применима в любых экологически неблагоприятных зонах. Исследования показывают, что некоторые растения позволяют очистить окружающую среду от металлов. Культивирование растений-гипераккумуляторов тяжелых металлов на загрязненных территориях позволяет очистить почву от избытка металлов.

Растения гипераккумуляторы в настоящее время подразделяются на восемь групп в зависимости от способности аккумуляции тяжелых металлов. Идеальные виды растений, которые будут использоваться в этом процессе должны иметь высокое производство биомассы, быстрый рост и легкую сборку, а также способность расти вне своей аборигенной области, так как почти 90% известных гипераккумуляторов являются эндемичными для металлосодержащих почв.

Фиторемедиация основана на удалении загрязнений из почвы с помощью таких механизмов, как фитоэкстракция, фитодеградация, ризофильтрация, фитостабилизация и фитоволизатирование, но механизмы, участвующие в регенерации тяжелых металлов, ограничены поглощением, адсорбцией, транспортом и транслокацией, секвестрацией в вакуолях, сверхнасыщением и, в некоторых случаях, улетучиванием. Поэтому поиск новых гипераккумуляторов очень важен.

Применение синтетических хелаторов и минеральных удобрений эффективно стимулирует аккумуляцию тяжелых металлов в органах растений за счет увеличения биодоступности и урожайности. Добавления

некоторых PGPR – бактериальных штаммов и микоризных грибов в ризосферу растений также стимулирует аккумуляцию тяжелых металлов в органах растений.

Одним из перспективных направлений фиторемедиации загрязненных тяжелыми металлами почв является использования трансгенных растений, специально спроектированных в качестве гипераккумуляторов.

Успехи в изучении гипераккумуляторов привели к идентификации около 500 таксонов, способных к гипераккумуляции различных элементов. Методы фиторемедиации разрабатывают и внедряют в разных странах мира, в том числе и в Казахстане.

Ключевые слова: фиторемедиация, тяжелые металлы, гипераккумуляторы, фитоэкстракция, городские почвы.

Information about authors:

Yelikbayev Bakhytzhan Koshkinbayevich, Professor of Satbayev University, Almaty, Kazakhstan; bek29k@gmail.com; http://orcid.org/0000-0002-1262-6524

Pagano Marcela Claudia, Association professor of Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil; marpagano@gmail.com; https://orcid.org/0000-0003-4764-6450

Jamalova Gulya Abaevna, Association professor of Satbayev University. Almaty, Kazakhstan; j.ga@bk.ru; https://orcid.org/0000-0002-4285-7390

REFERENCES

[1] Stroganova M.N. (2008) Urban soils: genesis, taxonomy and ecological significance (on the example of Moscow) / M.N., Stroganova // Diss. doct. biol. Sciences, in the form of a scientific report, M. 71 p. (in Russ.).

[2] Sintsov A.V. (2010) Soil cover of urbanized territories / A.V. Sintsov, A.N. Barmin. G.U. Adyamova. Astrakhan: ATC. 164 p. (in Russ.).

[3] Garapova R.A. (2011) Assessment of the ecological state of an industrial city and public health (on the example of Ust-Kamenogorsk) // Polzunovsky Bulletin. N 4-2. P. 72-75 (in Russ.).

[4] Stearns J.C., Shah S., Glick B.R. (2006) Increasing plant tolerance to metals in the environment. Ed. N Willey. Phytoremediation: Methods and Reviews. Humana Press. P. 15-26.

[5] Dixit R., Wasiullah M.D., Pandiyan K., Singh U.B., Sahu A., Shukla R., Singh B.P., Rai J.P., Sharma P.K., Lade H., Paul D. (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability. 7: 2189-2212.

[6] Sarwar N., Imran M., Shaheen M.R., Ishaq W., Kamran A., Matloob A., Rehim A., Hussain S. (2017) Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere. 171: 710-721.

[7] Maszenan A.M., Liu Y., Ng W.J. (2011) Bioremediation of wastewaters with recalcitrant organic compounds and metals by aerobic granules. Biotechnol Adv. 29 (1): 111-123.

[8] Brooks R.R., McCleave J.A., Schofield E.K. (1977) Cobalt and nickel uptake by the Nyssaceae. Taxon 26: 197-201 Brooks RR, Radford CC (1978) Nickel accumulation by European species of the genus Alyssum. Proc Roy Soc LondB. 200: 217-224.

[9] Jaffre T. (1977) Accumulation du manganese par des especes associes aux terrains ultrabasiques de Nouvelle-Caledonie. C R Acad Sci Paris D. 284: 1573-1575.

[10] Ali H., Khan E., Sajad M.A. (2013) Phytoremediation of heavy metals-concepts and applications. Chemosphere. 91: 869-881.

[11] Chandra R., Saxena G., Kumar V. (2015) Phytoremediation of environmental pollutants: an eco-sustainable green technology to environmental management. In: Chandra R (ed) Advances in biodegradation and bioremediation of industrial waste. CRC Press, Boca Raton. P. 1-30. https://doi.org/10.1201/b18218-2

[12] Mahar A., Wang P., Ali A., Awasthi M.K., Lahori A.H., Wang Q., Li R., Zhang Z. (2016) Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. Ecotoxicol Environ Saf. 26: 111-121.

[13] Muthusaravanan S., Sivarajasekar N., Vivek J.S., Paramasivan T., Naushad M., Prakashmaran J., Gayathri V., Al-Duaij O.K. (2018) Phytoremediation of heavy metals: mechanisms, methods and enhancements. Environ Chem Lett. 16: 1339-1359.

[14] Van der Ent A., Baker A.J.M., van Balgooy M.M.J., Tjoa A. (2013) Ultramafic nickel laterites in Indonesia (Sulawesi, Halmahera): mining, nickel hyperaccumulators and opportunities for phytomining. J Geochem Explor. 128: 72-79. doi:10.1016/j.gexplo.2013.01.009

[15] Baker A.J.M., Mcgrath S.P., Reeves R.D., Smith J.A.C. (2000) Metal hyperaccumulator plants: a review of the ecology and physiology of a biochemical resource for phytoremediation of metal- polluted soils. In: TERRY, N.; Banuelos, G. (Ed.) Phytoremediation of contaminated soil and water. Boca Raton: Lewis Publishers. P. 85-107.

[16] Ali H., Khan E., Sajad M.A. (2013) Phytoremediation of heavy metals - concepts and applications. Chemosphere. 91, 869-881.

[17] Sheoran V., Sheoran A.S., Poonia P. (2013) Phytomining of gold: a review. J Geochem Explor. 128, 42-50.

[18] Qu J., Luo C., Cong Q., Yuan X. (2012) Carbon nanotubes and Cu-Zn nanoparticles synthesis using hyperaccumulator plants. Environ Chem Lett. 10, 153-158.

[19] Qu J., Luo C.Q., Hou J.X. (2011) Synthesis of Zn nanoparticles from Zn-hyperaccumulator (Sedum alfredii Hance) plants. Micro Nano Lett. 6, 174-176.

[20] Baker A.J.M., Brooks R.R. (1989) Terrestrial higher plants which hyperaccumulate metallic elements a review of their distribution, ecology and phytochemistry. Biorecovery. N 1. P. 81-126.

[21] Salt D.E., Kramer U. Mechanisms of metal hyperaccumulation in plants. In: Raskin I, Ensley B (eds) Phytoremediation of Toxic Metals. John Wiley and Sons Inc., New York. 2000. P. 231-246.

[22] Prasad M.N. Practical use of plants to restore metal-polluted ecosystems. Plant physiology. 2003, 50, P. 764-780 (in Russ.).

[23] Willey N. (2007) Phytoremediation. Methods and Reviews. Ed. University of the West of England, Bristol, UK. Humana Press. 516 p.

[24] Dinh N., van der Ent A., Mulligan D.R., Nguyen A.V. (2018) Zinc and lead accumulation characteristics and in vivo distribution of Zn2+ in the hyperaccumulator Noccaea caerulescens elucidated with fluorescent probes and laser confocal microscopy // Environ Exp Bot. 147: 1-12.

[25] Yang X., Long X., Ni W., Fu Ch. (2002) Sedum alfredii: a new Zn hyperaccumulating plant first found in China // Chinese Sci Bull. 47, 1634-1637.

[26] Sun Y.B., Zhou Q.X., Wang L., Liu W. (2009a) Cadmium tolerance and accumulation characteristics of Bidens pilosa L. as a potential Cd-hyperaccumulator. J Hazard Mater. 161, 808-814.

[27] Pratas J., Favas P.J.C., D'Souza R., et al. (2013) Phytoremedial assessment of flora tolerant to heavy metals in the contaminated soils of an abandoned Pb mine in Central Portugal. Chemosphere. 90, 2216-2225.

[28] Salihaj M., Bani A., Echevarria G. (2016) Heavy metals uptake by hyperaccumulating flora in some serpentine soils of Kosovo. Global NEST J. 18: 214-222.

[29] Bini C., Maleci L., Wahsha M. (2017) Potentially toxic elements in serpentine soils and plants from Tuscany (Central Italy). A proxy for soil remediation. Catena. 148: 60-66.

[30] Yadava K.K., Gupta N., Kumar A., Reece L.M., Singh N., Rezania S., Khan S.A. (2018) Mechanistic understanding and holistic approach of phytoremediation: a review on application and future prospects. Ecol Eng. 120: 274-298.

[31] Galchenko S.V., Mazhaisky Yu.A., Guseva T.M., Cherdakova A.S. (2015) Phytoremediation of urban soils contaminated with heavy metals, ornamental flower crops // Bulletin of the Ryazan State University. S.A. Yesenin. 4 (49). P. 144-153. (in Russ.).

[32] Nascimento C.W.A., Xing B. (2006) Phytoextraction: a review on enhanced metal availability and plant accumulation. Scientia Agricola. 63: 299-311.

[33] Bhargava A., Carmona F.F., Bhargava M., Srivastava S. (2012). Approaches for enhanced phytoextraction of heavy metals. J Environ Manage. 105, 103-120.

[34] Raskin I., Smith R.D., Salt D.E. (1997) Phytoremediation of metals: using plants to remove pollutants from the environment. Curr Opin Biotech. 8, 221-226.

[35] Van Nevel L., Mertens J., Oorts K., Verheyen K. (2007). Phytoextraction of metals from soils: how far from practice? Environ Pollut. 150, 34-40.

[36] Kramer U. (2005) Phytoremediation: novel approaches to cleaning up polluted soils. Current Opinion in Biotechnology. Vol. 16: 133-141.

[37] McGrath S.P., Zhao F.J. (2003) Phytoextraction of metals and metalloids from contaminated soils. Current Opinion in Biotechnology. 14: 277-282.

[38] Szczyglowska M., Piekarska A., Konieczka P., Namiesnik J. (2011) Use of Brassica plants in the phytoremediation and biofumigation processes. Int J Mol Sci. 12, 7760-7771.

[39] Jabeen R, Ahmad A, Iqbal M. (2009). Phytoremediation of heavy metals: physiological and molecular mechanisms. Bot Rev. 75, 339-364.

[40] Seth C.S. (2012) A review on mechanisms of plant tolerance and role of transgenic plants in environmental clean-up. Bot Rev. 78, 32-62.

[41] Pollard A.J., Reeves R.D., Baker A.J.M. (2013) Review: facultative hyperaccumulation of heavy metals and metalloids. Plant Sci. 217218, 8-17.

[42] Greger M., Landberg T. (1999) Use of willow in phytoextraction. International Journal of Phytoremediation. 1: 115-123. doi: 10.1080/15226519908500010.

[43] Fischerova Z., Tlustos P., Szakova J., Sichorova K. (2006) A comparison of phytoremediation capability of selected plant species for given trace elements. Environmental Pollution. 144: 93-100.

[44] Salt D.E., Blaylock M., Kumar P.B.A.N., Dushenkov V., Ensley B.D., Chet L., Raskin L. (1995) Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. Biotechnology. 13 (2): 468-474.

[45] Chirakkara R.A., Cameselle C., Reddy K.R. (2016) Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants. Rev Environ Sci Biotechnol. 15: 299-326. https://doi.org/10.1007/s11157-016-9391-0

[46] Meagher R.B. (2000) Phytoremediation of toxic elemental and organic pollutants. Current Opinion in Plant Biology. 3: 153-162. doi: 10.1016/ S 1369-5266(99)00054-0.

[47] Sainger P.A., Dhankhar D., Sainger M., et al. (2011) Assessment of heavy metal tolerance in native plant species from soils contaminated with electroplating effluent. Ecotox Environ Safe. 74, 2284-2291.

[48] Zhang X., Xia H., Li Z., et al. (2011) Identification of a new potential Cd- hyperaccumulator Solanum photeinocarpum by soil seed bank-metal concentration gradient method. J Hazard Mater. 189, 414-419.

[49] Boyd R. (2010) Elemental defenses of plants by metals. Nat Edu Knowledge, 1, 6-9.

[50] Magdziak Z., Mleczek M., Kaczmarek Z., Golinski P. (2013) "Influence of Ca/Mg ratio and Cd2+ and Pb2+ elements on low molecular weight organic acid secretion by Salix viminalis L. roots into the rhizosphere." Trees-Structure and Function. 27 (3): 663-673.

[51] Auguy F., Fahr M., Moulin P., Brugel A., Laplaze L., El Mzibri M., Filali-Maltouf A., Doumas, P., Smouni A. (2013) "Lead Tolerance and Accumulation in Hirschfeldia incana, a Mediterranean Brassicaceae from Metalliferous Mine Spoils." Plos One. 8 (5).

[52] Petersen W., Bottger M. (1991) Contribution of organic acids to the acidification of the rhizosphere of maize seedlings. Plant Soil. 132: 159-163. Pilon-Smits E (2005) Phytoremediation. Annu Rev Plant Biol. 56: 15-39.

[53] Pereira B.F.F., Abreu C.A., Romeiro S., Lagoa A.M.M.A., Paz-Gonzales A. 2007. Pb-phytoextraction by maize in a Pb-EDTA treated Oxisol. Scientia Agricola. 64: 52-60.

[54] Gabos M.B., Abreu C.A., Coscione A.R. 2009. Edta assisted phytorremediation of a Pb contaminated soil: Metal leaching and uptake by jack beans. Scientia Agricola. 66: 506-514.

[55] Atabaeva S.D., Sarsenbaev B.A., Kirshibaev E.A., Nurzhanova A.A., Zhambakin K.Zh. (2011) Recommendations for phytoremediation of soils contaminated with heavy metals. Almaty, 56 p. (in Russ.).

[56] Yuan M., He H., Xiao L., Zhong T., Liu H., Li S., Deng P., Ye Z., Jing Y. (2013) Enhancement of Cd phytoextraction by two Amaranthus species with endophytic Rahnella sp. JN27. Chemosphere. 103: 99-104.

[57] Khan A., Sharif M., Ali A., Shah S.N.M., Mian I.A., Wahid F., Jan B., Adnan M., Nawaz S., Ali N. (2014) Potential of AM fungi in phytoremediation of heavy metals and effect on yield of wheat crop. Am J Plant Sci. 5: 1578-1586.

[58] Ma Y., Oliviera R.S., Nai F., Rajkumar M., Luo Y., Rocha I., Freitas H. (2015) The hyperaccumulator Sedum plumbizincicola harbors metal-resistant endophytic bacteria that improve its phytoextraction capacity in multi-metal contaminated soil. J Environ Manag. 156: 62-69.

[59] Backer R., Rokem J.S., Ilangumaran G., Lamont J., Praslickova D., Ricci E., Subramanian S., Smith D.L. (2018) Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Front Plant Sci. 9: 1473.

[60] Panin M.S. (2002) Zinc in the vegetation of the Irtysh River floodplain (Pollution as a result of the impact of the industrial enterprise OA Kazzinc). In the book "Heavy metals and radionuclides in the environment" Semipalatinsk. P. 174-186 (in Russ.).

[61] Kholodova V.P., Volkov K., Kuznetsov V.V. (2005) Adaptation to high concentrations of copper and zinc salts of crystal herb plants and the possibility of their use for phytoremediation // Plant Physiology. 2005. T. 52. P. 848-858 (in Russ.).

[62] Shevyakova N.I., Ilyina E.N., Kuznetsov V.V. (2008) Polyamines increase the phytoremediation potential of plants when cleaning soils contaminated with heavy metals // Reports of KazNU. General biology.

[63] Atabaeva S.D., Sarsenbaev B.A., Kenzhebaeva Sh.K., Kirshibaev E.A., Usenbekov B.N., Asrandina S.Sh., Danilova A.N., Kotukhov Yu. A., Kalmykov E.L. (2008) "Features of the removal of heavy metals by wild plant species" // Bulletin of KazNU. P. 13-16 (in Russ.).

[64] Atabayeva S.D., Sarsenbayev B.A., Kenzhebayeva Sh.K., Usenbekov B.N., Asrandina S.Sh., Kirshibayev E.A., Kalmykov E.L, Danilova A.N. (2006) Metal accumulation ability of grass species of Kazakhstan flora and the possibility using them for phytoremediation // New Research on the Environment and Biotechnology. Nova Science Publishers, Inc., New York. P. 1-15.

[65] Tasekeev M.S. (2004) Bioremediation of toxic industrial waste // Industry of Kazakhstan. N 10. P. 59-63 (in Russ.).

[66] Elikbaev B.K., Musina U.Sh., Dzhamalova G.A., Musina G.Sh., Toganbai A.N., Kurbanova L.S., Sarsenbaev S.O., Sybanbaeva M.A. (2017) Bioremediation of oil-contaminated soils based on natural and technogenic carbon-containing bioactivator - Koksu shungite // Bulletin of KazNU. Biological series. N 4 (73). P. 141-152. ISSN 1563-0218 (in Russ.).