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BIOTECHNOLOGY FOR IRON ORE DUMP REMEDIATION BY CREATING STEADY PLANTS ASSOCIATIONS

A method for iron-ore dump biological remediation by planting steady multicomponent grassy associations similar to the natural steppe biogeocenotical structures has been developed. The models of fescue-feather-mixed grass associations for different types of dumps have been presented. The biotechnology of remediation has been suggested.

Keywords: biotechnology, remediation, dumps, plant associations, and Kryvyi Rih area.

RELEVANCE OF THE PROBLEM

As a result of iron ore extraction operations that have been lasted for longer than half a century, in the Kryvyi Rih region, the natural landscapes are transformed into dangerous man-made objects: quarries, spoil dumps and tips, slag heaps, sagged areas, landslides, etc. These man-caused factors affected the geomorphological and hydrological structure of the region, which, consequently, has entailed climate fluctuations, as well as changes in the soils and vegetation. The total area of spoiled and contaminated lands in Kryvyi Rih region reaches more than 35 thousand hectares [1, 2, 3, and 4]. For many years, these lands remain a source of adverse impact on the environment. Remediation is one of the measures to overcome this negative effect, to restore the land productivity, and to ensure the environmental sustainability of the region.

One of the priorities of the Kryvyi Rih Botanical Garden of the NAS of Ukraine since its creation till nowadays is the development of methods for biological remediation of contaminated lands of different types [5]. To mitigate the negative impact of slag dumps on the environment, a technique for comprehensive differentiated biological consolidation of their dusty surfaces has been proposed. This technique is noteworthy for the fact that it does not require any radical improvement of substrates. In the wetlands, *Phragmites australis* (Cav.) Trin. ex Steud. (common reed) is successfully planted on the dumps without any fertilization or other supplements due to its ecological and biological properties. To consolidate the dry areas *Leymus sabulosus* (M. Bieb.) Tzvel. (wild rye) is used [6, 7, 8, and 9].

To mitigate the harmful effects of quarries on the environment it is recommended to plant *Robinia pseudoacacia* L., *R. viscosa* Vent., *Rhus typhina* L. (staghorn sumac), *Armeniaca vulgaris* Lam. (apricot), *Populus italica* (Du Roi) Moench (pyramidal poplar), etc. [10, 11].

To optimize the situation on the iron ore dumps and to minimize their adverse impact on the environment a technique for preparation of dumps for planting. This technique provides for the replacement of mining engineering stage of remediation of contaminated lands by structural or functional control by reshaping with the use of mining machinery and creating appropriate areas on them in the course of dumping [12].

For the biological remediation of dumps the priority is given to forestry that involves the creation of artificial forest plantations of sanitary importance. For this purpose, the young plants of *Robinia pseudoacacia, Populus italica, Cerasus mahaleb* (L.) Mill, *Hippophae rhamnoides* L., *Elaegnus angustifolia* L., *Ulmus pumila* L., *Betula pendula* Roth, *Pinus sylvestris* L., *Pinus pallasiana* D. Don and others are used [13, 14, 15, 16, 17, and 18].

However, the creation of sustainable motley-grass culture phyto-geneses on the dumps was disregarded for a long while [19, 20]. So, today, the development and implementation of biotechnologies for the remediation of iron ore heap by herbaceous plants remain relevant. To this end, in 2014, the Kryvyi Rih Botanical Garden of the NAS of Ukraine has implemented an innovative R&D project "Development and Implementation of a Biotechnology for Creating Sustainable Plant Associations on Contaminated Lands of Kryvbas".

GENERAL DESCRIPTION OF IRON ORE TAILINGS IN KRYVBAS REGION

The area of the dumps in Kryvyi Rih region exceeds 6 thousand hectares. The dumps consist of 3 billion m^3 rocks. The dump height varies from 40 to 90 m [2, 3, and 4].

The Kryvyi Rih quarries consist mainly of Quaternary deposits (Wurm, Rissian, and Mindelian clay loams); Tertiary deposits (Cimmerian, Pontian, and Sarmatian clays and sands), as well as of Precambrian crystalline rocks (ferruginous jaspilites and various shales). Rock-forming minerals are quartz, iron-magnesium and chlorite-biotite silicates and ore minerals (magnetite, hematite, goethite, and martite).

The chemical composition of dumps is characterized by a significant content of silicon earth (38—55 % or more) and iron oxide (14—53 %) and a small amount of phosphorus (0.08—0.27 %). The reaction of aqueous extract (*pH*) is 6.8—8.2. Most rocks are characterized by low content of mineral nutrients in the form accessible for plants. Only a few rocks (eg., Loess-like loam, sand quartzite, apatite-containing rocks) have an organic matter content of 0.8—8.1 %; carbonate share of 0.25 %; humus share of 0.02 %; and potassium content of 1.0—5.0 mg/100 g [2, 3, 4, and 21].

As a result of the fact that the mining companies fail to respect the requir ements for selective dumping the composition of dumps is very diversified as they contain loess and loess-like loam, sandy and loamy clays, limestone and malmstone loose rocks, raw shale, ferruginous quartzite fragments, etc. So, it is very difficult to classify unambiguously the dumps by their composition, since one dump can have plots with different soils.

The specific features of dumps in Kryvyi Rih region are: 1) the prevalence of substrates with mixed grading (clay, loam, rock); 2) a large number of dumps with the prevalence of ferruginous quartzite and shale; 3) significant enrichment of substrates with iron oxides; 4) extremely rigorous thermal conditions and lack of moisture; 5) very low trophic properties.

Among the overburden rocks in Kryvyi Rih region, the most favorable for plant growth and development is non-saline soils: loess, loess-like loam, non-saline clay. Less favorable are malmstone, limestone, marble, and amphibolite. Shale rock is unfavorable [2, 3, 4, and 21].

SPECIFIC FEATURES OF NATURAL COLONIZATION OF IRON ORE TAILINGS IN KRYVBAS REGION

For developing methods and techniques for biological remediation of dumps, the results of their natural colonization by plants are very important. As a result of dumping, a large number of edaphotopes that determine the course of natural colonization appear. The soils that are a part of edaphotope are known to have different chemical, physical, mechanical, and hydrological properties. In addition, the area having similar composition may differ markedly in terms of stability and topography (steep slopes, exposure). As mentioned above, a common feature of all overburden rocks is a lack of organic matter and a low content of mineral nutrients in the form accessible for plants. So, the intensity of natural colonization of dumps is determined by the type of substrate, its physical and mechanical properties, topography, moisture and temperature conditions. At the initial stages of dump colonization, seeds of trees and herbaceous plants are brought from the surrounding areas. These trees and plants show pioneering features: a high germination energy, a long period of keeping the similarity, intensive root growth, drought resistance, high ecological plasticity, etc. [10, 11, 14 20, and 22].

Natural colonization of loamy and clay heaps begins in the first year after dumping, with the formation of pioneer vegetation. Individual plants are reported: *Oberna behen* (L.) Ikonn., *Erucastrum armoracioides* (Czern. ex Turcz.) Cruchet, *Convolvulus arvensis* L., *Conyza canadensis* (L.) Cronq., *Ambrosia artemisiifolia* L., etc.

The 3—5-year tailings are spotted by vegetation, with wild grass prevailing. The number of species increases to 30. The 5—10-year tailings are planted for 30 %, with perennial rootstock, tussock or bunch-type grass (*Elytrigia repens* (L.) Nevski, *Poa angustifolia* L., *P. compressa* L., *Bromopsis riparia* (Rehman) Holub, *Festuca valesiaca* Gaudin, *Koeleria cristata* (L.) Pers. (*K. gracilis* Pers.), etc.; biennial and perennial herbs (*Melilotus officinalis* (L.) Pall., *M. albus* Medik., *Medicago romanica* Prodan, *Reseda lutea* L., *Erysimum diffusum* Ehrh., *Seseli campestre* Besser, *Salvia tesquicola* Klokov et Pobed., *Stachys recta* L. replacing the wild grass.

The 20-year tailings, usually, have almost completely formed steppe-type vegetation. The coverage reaches 60—80 %. The tussock and bunch-type grass (*Stipa lessingiana* Trin. et Rupr., *S. capillata* L., *Festuca valesiaca*, *Koeleria cristata*, *Poa angustifolia*) ousts the rootstock one, with perennial legume crops (*Medicago romanica*, *Lotus ucrainicus* Klokov, *Astragalus onobrychis* L., *Vicia angustifolia* Reichard, *V. cracca* L., *Securigera varia* (L.) Lassen, etc.) having a significant share.

Natural colonization of iron ore, quartzite, and fissile tailings. This type of tailings is colonized very slowly. The first plants appear in 5—10 years after dumping. Among them, there are, mainly, singular wild plants: *Erucastrum armoracioides*, *Reseda lutea*, *Oberna behen*, *Melilotus albus* Medik., *Hieracium virosum* Pall., *Chaenorrhinum minus* (L.) Lange, *Kochia scoparia* (L.) Schrad., *Conyza canadensis*, *Polygonum aviculare* L. Later, as hypergenesis enhances, the physical, chemical, and agrochemical properties of these substrates improve.

On 10—15-year tailings, there are favorable conditions for colonization by ruderal plants: *Artemisia absinthium* L., *Salsola tragus* L., *Echium vulgare* L., *Crepis tectorum* L., *Conyza canadensis*, *Bromopsis inermis* (Leyss.) Holub, and *Melilotus albus*.

Eventually, the number of non-perennial and biennial ruderal plants decreases, while that of steppe-type plants (*Festuca valesiaca*, *Koeleria cristata*, *Agropyron pectinatum* (M. Bieb.) Beauv., *Melica transsilvanica* Schur, *Elytrigia repens*, *Medicago romanica*, *Crambe pontica* Steven ex Rupr. (*Crambe maritima* L.), *Gypsophila perfoliata* L., etc.) increases [19, 21, and 22].

Natural colonization of lime heaps is a very slow process. At the initial stage, only a couple of plants per 1 m^2 occurs. First of all, they are represented by pioneer species: *Oberna behen*, *Artemisia absinthium*, *Melilotus albus*, and *Diplotaxis muralis* (L.) DC. Later, typical steppe species appear: *Stipa capillata*, *S. lessingiana*, *Poa angustifolia*, *Poa compressa*, *Bromopsis inermis*, *Melica transsilvanica*, *Bothriochloa ischaemum* (L.) Keng., *Salvia nutans* L., *S. austriaca* Jacq., *S. aethiopis* L., *Astragalus onobrychis* L., etc. Typical calciphytes occur as well: *Dianthus pseudoarmeria* M. Bieb., *Linum czerniaevii* Klokov, *Convolvulus lineatus* L., and *Jurinea brachycephala* Klokov [20, 22, and 23].

The study of natural colonization of iron ore tailings in Kryvyi Rih region has showed that all of them are suitable for vegetation but differ by rate of colonization. The highest rate is reported for the tailings dumped with loess, loess-like rocks, and clay loams, the colonization of ferruginous quartzite and fissile tailings mixed with clay loams takes a longer time; the lime heaps show a quite low rate of colonization; and the iron-quartzite-fissile tailings have the lowest colonization rate. A clear evolution of colonization stages, which resembles the reclamation of steppe vegetation on broken soils has been observed. At the initial stages of colonization, the syngenesis is of ruderal type, with various pioneer species prevailing. Among them, there are, chiefly, *Oberna behen*, *Conyza canadensis*, *Ambrosia artemisiifolia*, *Iva xanthiifolia* Nutt. and other weed plants. Eventually, micro-associations of non-perennial weeds are replaced by perennial herbs and later, by long-rooted, tussock, and bunch-type grass. At all stages of colonization of all types of tailings, dendroid plants play an important role [10, 11, 14, 15, 17, and 22] (Figs.1, 2).

The studies have showed that the syngenesis on the tailings has several specific features: discreteness, slow and asynchronous colonization, combination of species belonging to different environmental groups, simplified structure, mosaic pattern, and trend to remediation of steppe associations.

MODELS OF MULTICOMPONENT MOTLEY GRASS-FESTUCA-STIPA ASSOCIATIONS

The first research related to creating the culture phytocenoses of natural flora on iron ore tailings in the Kryvyi Rih region was initiated by the Kryvyi Rih Botanical Garden (at that time, the Kryvyi Rih Department for Optimization of Man-Made Landscape of the Donetsk Botanical Garden) in 1975, when *Chupryna* and *Plugina* sowed the seeds of natural species on three lots of tailing of Pershotravnevyi quarry with prevailing clay loam mixed with ferruginous quartzite and fissile [20]. *Kucherevskyi* and *Mazur* continued the research [10, 17]. The experiment has established that for remedying the vegetation on iron ore tailings, perennial tussock and bunchy grass (*Stipa* L., *Festuca* L., *Koeleria* Pers., *Melica* L. and steppe motley grass of *Salvia* L., *Crambe* L., *Melilotus* L., *Medicago* L., *Gypsophila* L.., etc.) should be preferred

Hence, upon the results of research of spontaneous colonization of various types of tailings and long-time research of several steppe species on dumped substrates, some motley grass-Festuca-Stipa associations based on natural zonal biogeocenotic structures were developed for main types of tailings.

1. Model of motley grass-Festuca-Stipa associations for the remediation of iron ore tailings composed of potentially fertile rocks and soils: loess, loess-type clay loam, loose non-saline clays.

The tailings of this type are the most favorable for growth of plants. These substrates are suitable for designing plant associations that are mostly approximated to the zonal ones by their structural and functional properties, sustainability, and producing capacity. This can be reached by combining different zonal dominant species. The proposed design of plant associations has a polydominant structure: *Stipa lessingiana* + *S. ucrainica P. Smirn.* + *S. pulcherrima* K. Koch (*S. grafiana Steven*) + *S. capillata* + *Festuca valesiaca* + + *Koeleria cristata* + motley grass: *Melilotus albus* + *Salvia tesquicola* + *Medicago romanica* + + *Crambe pontica*. Both separate species and blends of Stipa can be used as dominants.

The implementation of this model enables excluding intermediary stages of spontaneous remediation of vegetation for accelerating the creation (for 5—7 years) of multicomponent 2—3-layer culture cenosis with a design coverage of 60—80 %. Starting with 2—3 years they replenish the seed stock, which enables a significant expansion of colonization over new territories.

2. Model of motley grass-Festuca-Stipa associations for the remediation of iron ore tailings composed of hardly suitable rocks and soils: loess, loess-like clay loam, quartzite and fissile: *Stipa lessingiana* + *S. ucrainica* + *S. capillata* + *Festuca valesiaca* + *Melica transsilvanica* + + *Koeleria cristata* + motley grass: *Salvia tesquicola* + *Crambe pontica* + *Medicago romanica* + + *Hyssopus officinalis* L.

The creation of dense vegetation cover on these tailings is quite slow as compared with the previous type. The generative period of grasses comes later, in 3—5 years. The 7—10-year plant associations have 2-layer thinned structure; their design coverage is under 50—60 %. Steppe culture cenoses similar to the natural ones are formed in 10—15 years.

Fig. 1. Natural colonization of ferruginous quartzite and shale dump by *Populus italica*

Fig. 2. Natural colonization of ferruginous quartzite and shale dump by grass

3. Model of motley grass-Festuca-Stipa associations for the remediation of iron ore tailings composed of hardly suitable rocks and soils: quartzy sand and glauconitic loamy sand. *Stipa borysthenica* Klokov ex Prokudin + *Festuca valesiaca* + *Koeleria cristata* + *Leymus sabulosus* (M. Bieb.) Tzvelev + motley grass: *Crambe pontica* + *Gypsophila perfoliata*.

The preferred plants for this type of tailings are *Stipa borysthenica* and *Leymus sabulosus* that are species planted on sandy soils. This vegetation cover starts to perform its erosion-resistant function in 7—10 years. The design coverage does not exceed 50—60 %.

4. Model of motley grass-Festuca-Stipa associations for the remediation of iron ore tailings composed of hardly suitable rocks and soils: limestone and marl-stone with clayish minerals: *Stipa asperella* Klokov et Ossycznjuk + + *S. ucrainica* + *S. pennata* L. + *Festuca valesiaca* + *Bothriochloa ischaemum* + motley grass: *Diplotaxis tenuifolia* + *Melilotus officinalis* + *Hyssopus officinalis*.

The associations start to resist erosion and to perform protective functions in 7—10 years, with 2—3-layer vegetation cover similar to the zonal one with a design coverage of 60—70 % formed in 12—15 years.

5. Model of motley grass-Festuca-Stipa associations for the remediation of iron ore tailings composed of rocks: fissile and unoxidized quartzite: *Stipa graniticola Klokov* + *S. ucrainica* + *Festuca valesiaca* + *Melica transsilvanica* + + motley grass: *Crambe pontica* + *Gypsophila perfoliata* + *Hyssopus officinalis*.

The tailings of rocks are the most tough to be remedied. At the initial stages, Stipa sprouts are rare and oppressed. The plants reach their generative period in 5—7 years and produce additional seeds. The associations start to perform their protective functions in 10—12 years. The sustainable vegetative cover with a design coverage up to 60 % is formed in 15—18 years.

The common thing for all the models is the presence of tussock grass (*Stipa, Festuca* or *Koeleria*) therein. Implementation of these models enables excluding initial stages of spontaneous colonization of the tailings and, therefore, speeding up significantly the creation of sustainable multicomponent plant associations similar to the natural one. As soon as the plants reach their generative period they start to produce seeds and, due to spontaneous drilling, to expand the territories under vegetation.

BIOLOGICAL TECHNIQUE FOR REMEDIATION OF IRON ORE TAILINGS IN KRYVYI RIH REGION

The biotechnology includes the collection of seeds of recommended plants in natural habitat or in special seedbeds of phyto-ameliorative species, in accordance with terms of seed maturation: the majority of *Stipa* species: end of May—June, *Stipa capillata*: end of August—September, *Festuca valesiaca*: end of May—June, *Koeleria cristata*: end of May—June, *Leymus sabulosus*: June—July, *Bothriochloa ischaemum*: August, *Salvia tesquicola*, *Crambe pontica*: June—July, *Medicago romanica*: July, *Hyssopus officinalis*: July—September, *Gypsophila perfoliata: September*, *Melilotus albus*: September, *Diplotaxis tenuifolia*: July (Fig. 3).

According to the model proposed, freshly collected seeds of *Stipa* species together with awns are sown in May—June on the heap surface without wrapping into substrate with a seed consumption of 5—10 kg/ha (Fig. 4). The *Stipa* seeds deepen into the substrate by themselves, due to their hygroscopic properties. If necessary, in October—November or in March—April of the next year, additional *Stipa* seeds are be sowed with a seed consumption of 3—5 kg/ha. Under favorable weather conditions, *Stipa* seeds germinate within the year of sowing and, at the end of the growing season, reach the stage of tillering. In dry years, the seeds massively germinate in the spring of the next year and, during the first year of growth, pass through all age phases of virginile stage of biomorphogenesis.

In autumn (or spring of the next year), in the same areas, seeds of other xeromesophilous tus-

Fig. 3. Collection of *Stipa* species seeds in the seed field of Kryvyi Rih Botanical Garden

sock and bunchy perennial grasses are sown in accordance with models proposed: *Festuca valesiaca*, *Koeleria cristata*, *Melica transsilvanica*, *Bothriochloa ischaemum*with a seed consumption of 1—3 kg/ha of each species and seeds of xerophilous non-perennial or perennial phyto-ameliorative herbaceous species: *Salvia tesquicola*, *Crambe pontica*, *Medicago romanica*, *Hyssopus officinalis*, *Melilotus albus* and *M. officinalis*, *Gypsophila perfoliata*, *Diplotaxis tenuifolia* , etc. No additional measures to care for the plants are taken. Since reaching the generative period the *Stipa* and other species start to expand spontaneously over the surrounding territories. In the third or fifth year, the design vegetation cover on different types of substrates reaches 30—70 %. The composition of vegetation cover is similar to zonal steppe plant associations.

Fig. 4. Sowing of *Stipa* species seeds on ferruginous dump of Pershotravnevyi quarry of *Pivnichnyi GOK* PJSC

Combining the technology for creating the vegetation cover on different types of iron ore dumps with the natural colonization enables achieving a significant environmental effect from remediation and reducing the cost of its implementation. Environmental effectiveness of this biotechnology has been proved on iron ore dumps of Pershotravnevyi quarry of *Pivnichnyi GOK* PJSC and on a dump of the Lenin mining administration (Figs. 5, 6) [24, 25].

Fig. 5. *Stipa ucrainica* on a remedied area of the dump of Pershotravnevyi quarry of *Pivnichnyi GOK* PJSC

Fig. 6. *Stipa lessingiana* on a remedied area of the dump of Lenin Mining Administration

CONCLUSIONS

1. The diversity of mineral ores and mines in the Kryvyi Rih region has been established to cause the formation of different types of tailings: they can be composed of loess, loess-like clay loam, raw shale, sand and loamy sand, Cretaceous and malmstone loose rocks, fragments of ferruginous quartzite or mixed rocks.

2. The study of colonization of iron ore heap has showed that among the types of tailings, the most favorable for the plant development are loess, loess-like loam, and non-saline clays. Malmstone rocks (limestone, marble) are less suitable; conditionally unsuitable rocks are raw shale and ferruginous quartzite. The fastest colonization has been reported for the heaps composed of loess and loess-like loam; very slowly colonized tailings are those consisting of ferruginous quartzite and shale mixed with loam; limestone heaps are colonized with a slowly pace; and the ferruginous quartzite and shale rocks have been established to show the slowest rate of colonization.

3. The developed technique for biological remediation of iron ore dumps excludes mine engineering stage of remediation, as well as agroengineering and agrochemical improvement of substrates. It includes planting of grasses, dominants, and subdominants of steppe ecosystems.

4. The implementation of the developed remediation method reduces time of dump reinforcement with plants as compared with natural colonization by 15—20 years for loess loam; by 30—40 years for ferruginous quartzite and shale mixed with loess-like loam; by 20—30 years for limestone.

5. The biotechnology for remediation of Kryvyi Rih iron ore heaps by creating a motley-grass-*Festuca-Stipa* associations similar to zonal biogeocenotic structures has been implemented on the dump of Pershotravnevyi quarry of *Severnyi GOK* PJSC and on the dump of Lenin mining administration.

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БІОТЕХНОЛОГІЯ РЕКУЛЬТИВАЦІЇ ЗАЛІЗОРУДНИХ ВІДВАЛІВ ШЛЯХОМ СТВОРЕННЯ СТІЙКИХ ТРАВ'ЯНИСТИХ РОСЛИННИХ УГРУПОВАНЬ

Розроблено метод біологічної рекультивації залізорудних відвалів шляхом створення стійких багатокомпонентних трав'янистих угруповань, подібних до природних степових біогеоцеотичних структур. Наведено моделі різнотравно-типчаково-ковилових угруповань для різних типів відвалів. Запропоновано біотехнологію рекультивації.

Ключові слова: біотехнологія, рекультивація, відвали, рослинні угруповання, Криворіжжя.

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Разработан метод биологической рекультивации железорудных отвалов путём создания устойчивых многокомпонентных травянистых сообществ, подобных природным степным биогеоценотическим структурам. Приведены модели разнотравно-типчаково-ковыльных сообществ для разных типов отвалов. Предложена биотехнология рекультивации.

Ключевые слова: биотехнология, рекультивация, отвалы, растительные сообщества, Криворожье.

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