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REVIEW OF APPLIED RESEARCH ON PHYTOREMEDIATION IN ECOLOGICAL BALANCE RECOVERY ON MINING-DISTURBED LANDS IN GLOBAL SUBSOIL USE*

The article presents the latest findings concerned with environmental problems and solutions in the mining industry using technologies of phytoremediation based on the natural ability of plants to accumulate toxic elements, including heavy metals, in their biomass. The review of applied ecological research shows that phytoremediation and absorption of toxic elements is implemented in all climate zones on all continents. Recent studies in phytoremediation pay much attention to introduction of organic substances in polluted soil to decrease or increase effect of accumulation of heavy metals by plants. Each research work actualizes removal of heavy metals from contaminated soils using indigenous plants.

Keywords: *world mining industry, mining ecology, phytoremediation, plant biosystems, heavy metals, toxic elements, contaminated soil, ecological balance recovery*
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Introduction

Economic activities of humans in the field of subsoil use has lead by now to the substantial cumulative impacts. People on all habitable and populated continents perform large-scale solid mineral mining. Processing of extracted mineral resources is carried out in close proximity to mining sites. Such activities destroy all biospheres on the Earth, and, first of all, the soil mantle. Soils accumulate all toxic elements, including heavy metals. One of the latest trends of ecological balance recovery on mining-disturbed lands is phytoremediation. This area of research is being generated by professional teams of scientists-practitioners in all mining regions of the world for the recent 35–40 years. Consequently, there is an objective cause to systematize the accumulated knowledge in the area of stimulating ecologization of mining using technologies of phytoremediation. Technological progress follows an ascending tract, and our review pays close attention to the latest research and findings [1–55].

Review of research on phytoremediation toward ecological balance recovery in the regions of mineral deposits which are mined-out or being mined

Vector of our analytical review goes from the countries in the northern hemisphere of the Earth to the countries in the southern hemisphere, and from the western to the eastern hemisphere. With respect to continents, our pathway runs from North America to South America, to Europe, then to Africa and finally to Asia.

In the areas of North and South America, mineral extraction has been pulled up in recent two centuries. At the present time, the deepest open pit mines in the world are operated here [56]. In the USA, within the Oronogo-Duenweg Mining Belt, plants *Panicum virgatum* and *Bouteloua dactyloides* are recommended for the accumulation of Cd and Zn in case of soil application with biochar and cattle manure [1]. For the climatic conditions in the countries in Central America, for biomass to accumulate Fe, Pb, Zn and Cu in soil in mining areas, it is suggested to use *Gliricidia sepium*—a tree to 15 m high [2]. Widely spread in Mexico, *Dodonaea viscosa* can accumulate Zn, Cu, Cd, Pb and Fe, and is tolerable to these metals. These two factors enabled recommending the plant for the use in phytoremediation on mining-polluted lands [3]. It is also found that plant *Blepharidium guatemalensfor* can be recommended for biomass to accumulate nickel with a view to producing it at a commercial scale [4]. For the better establishment and exaggerated growth of *Prosopis laevigata* used in reclamation of tailings dumps in Mexico, the reclamation layer is introduced with biochar from coconut fiber and corn ears, which binds and decreases concentration of Cu, Pb, Cd, Fe and Mn in this layer [5]. In Brazil *Urochloa brizantha* is set out to accumulate As on the surface of iron ore tailings dumps. Herewith, it is recommended to add the surface layer with phosphogypsum [6]. Furthermore, for open pit iron ore mining areas, the use of *Paspalum densum* is advised to recover Cu, Fe, Zn and Mn from soil and to accumulate these elements in biomass [7]. For the land polluted with copper in Brazil, it is recommended to perform phytoremediation using *Brassica juncea* with addition of biochar from orange pomace in soil [8]. In Argentina, gold recovery factories heavily polluted land in the neighborhood with As, Cu, Cd and Zn. The studies show that such plants as *P. tetracantha*, *L. cuneifolia* and *P. flexuosa* are the bio-accumulators of the listed toxic elements. The use of these plants can enlarge grass lands for local farm animals [9].

In Europe large-scale mineral mining gets back centuries in such counties as Spain, Italy, Greece etc. [56]. In Spain researchers found out that efficiency of accumulation of As and Hg by plants *Medicago sativa* increased when soil was added with organic fertilizer [10]. The same effect was observed in case of planting of *Sinapis alba* with simultaneous soil application with biochar prepared through pyrolysis of manure. As a result, efficiency of accumulation of Zn, Pb, As, V and Cd by the mentioned plant grew [11]. Moreover, it is revealed that on low-nutrient and polluted soil in Spain, plants *Erica australis* L. and *Nerium oleander* L. can grow and accumulate large concentrations of Cu, Cd, Pb and S, while *A. serpyllifolium* is recommended for the commercial agromining of Ni, Sr and Ba through phytoremediation [12, 13]. In the northeast of Catalonia, Spain, *Sinapis alba* growing in the area of an ancient mine accumulates Cd, Cu, Pb and Zn in the presence of zinc-tolerant bacteria *Bacillus*, *Pseudomonas* and *Serratia* [14]. In Romania, in a mineral mining region, the analysis of accumulation of toxic elements by plant *Ocimum basilicum L*. shows that Cd, Co, Cr and Pb accumulate in roots, and Cu, Ni and Zn concentrate in blossom of this plant. The plant is recommended for the use in technologies of phytoremediation

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[15]. Italian researchers find out that cultivar *Spagnolo* in family *Cynara cardunculus* is a hyperaccumulator of Cd, Cu, Fe, Pb, Sb and As, and is also tolerable to other heavy metals [16]. This research also shows that *Helichrysum italicum subsp. microphyllum* concentrates Zn, Pb and Cd, but this effect decelerates in polluted soil introduced with organic compost [17]. In France, on the land polluted by lead mining, accumulation of Pb and As by plant *Oxalis pes-caprae* L. increases when soil is applied with biochar and compost [18]. In Kosovo in Europe, it is suggested to use *Salix purpurea* to remove Zn, Pb, Ni, Cd, Cu, As, Co and Cr from soil in a mining area [19]. In Great Britain, it was studied how *Agrostis tenuis* accumulated Pb. The plant adapted for lead contamination. The metal totally accumulates in the aboveground portion of the plant, which allows its gathering by agricultural machines [20]. At the juncture between Europe and Asia, in Armenia, on the polluted land in mining areas, high concentrations of Cu reduce substantially owing to planting of *A. absinthium* with addition of ammonium nitrate together with citric and malic acids in soil [21]. In the area of another mine, accumulation of Cu and Mo in the roots of *Melilotus officinalis* was noticed and examined, while plant *A. retroflexus* concentrated Cu and Mo in the aboveground portion. Addition of chelates in soil stimulated absorption of Cu and Mo by these plants [22].

Large transcontinental corporations on the continent of Africa develop numerous deposits of solid mineral resources [56]. The international research carried out in the similar climatic conditions in South Africa and China reveals that plant *Pteris vittata* enhances absorption of V and Fe in the presence of endophytic bacteria *Serratia marcescens*. The effect is boosted through introduction of phytic, malic and oxalic acids in contaminated soil [23]. For all provinces of copper and lead mining in South Africa, it is recommended to use plant *Helichrysum splendidum* in technologies of phytoremediation [24]. In Botswana, for the purposes of reclamation of tailings dump, tree *Colophospermum mopane* is selected. On the other hand, high concentrations of Mn, Cr, Pb, Zn, As, Pt, Li, Sn, Co, Cd, Mo, Cu, Fe and Ni greatly decelerate development of nursery plants of these trees. It was found that addition of cattle manure in polluted soil substantially decreased mobility of the toxic elements and concurrently increased the biomass of the planted trees [25]. Also in Botswana, three local acacia cultivars *Acacia albida*, *Acacia luederitzii* and *Acacia tortilis* were used in reclamation of tailings dumps. A set of improvers of mycorrhiza and fly ash applied to the surface layer of tailings dumps facilitated reduction of accumulation of Cu, Ni, Pb, Mn and Zn in the biomass of the shrub vegetation and stimulated survival rate of the planting stock [26]. In Zambia the soil pollution with Cu, Fe, Mn and Zn after copper mining is suggested to reduce by planting *Brachystegia longifolia* [27]. In the Republic of South Africa, bermudagrass and African daisy are recommended as accumulators of Cd, Co, Mn, Ni and Zn. The accumulation effect is boosted through beating-up of local aloe cultivars *A. burgersfortensis* and *A. castanea* [28]. In Ethiopia plant *Phytolacca dodecandra* is advised to use in technologies of phytoremediation and in removal of Pb and Cd from the polluted soil [29].

Countries of Asia produce nearly all possible minerals at thousands of operating mines [56]. In the area of South Ural in Russia, possessing high mining and metallurgy potential, it is found that the plants of elder and barberry are the most tolerable to the polluted soils and can accumulate heavy metals [30]. It is advised to develop massively technologies of bioremediation and phytoremediation using plants and microorganisms in the mining industry [31]. In an area of operating lead mines in Iran, the dominant plant is *Cynodon dactylon*. On the polluted land, the plant was inoculated with a mix of arbuscular mycorrhiza and rhizobacteria, which stimulate plant growth, together with epigeic earthworms (*Eisenia fetida*). Accumulation of Pb in the dominant plant increases by many times as a result [32]. In the Angouran Mine area in the northwest of Iran, with a view to removing Zn, Pb, Cr, Cd and Co from soil, 25 native plant species were selected. Out of the sampling, *Marrubium cuneatum*, *Psathyrostachys fragilis*, *Stipa arabica* and *Verbascum speciosum* were recommended for phytoremediation [33]. In Pakistan, in the mining province of Hayatabad, phytoremediation potential of 17 wild plants was evaluated. Plants *Erigeron conyzanthus* and *Chenopodium murale* accumulated Ni, Cu, Cr, Cd and Pb in their roots, while *Solanum xanthocarpum* and *Argemone Mexicana* concentrated Pb and Cr in the aboveground portion [34]. In the Hyber Pahtunhwa province in Pakistan, in the region of large-scale marble production, the scope of the research embraced 220 local plants. Out of the sampling, 19 plants were selected as hyperaccumulators and phytostabilizers of toxic elements (Cr, Ni, Cu, Mn, Zn, Fe, Co, Cd, Ca and Mg) [35]. In a copper mining area in Oman, it is found that the castor-oil plant can accumulate copper in the root system. The studies allowed the correlation between copper concentration in the roots and phosphorus addition in the polluted soil. The plant is recommended for using in phytoremediation of soils polluted with copper [36].

In China, it is found that ryegrass, wormwood and cup plant absorb Pb and Zn in the presence of glomalin-binded soil protein [37]. The other research of Chinese scientists reveals capability of Lucerne to accumulate V in roots and stems when polluted soil is applied with biochar with iron sulfate [38]. For a zinc mine in Xuzhou in China, it is proposed to extract Cd from the contaminated soil using plant *S. alfredii* and agrotechnical measures (root cutting) [39]. In South China, fern cultivar *Dicranopteris linearis* growing on old tailings dumps is classified as a hyperaccumulator of rare earths La, Nd, Ce and Pr. Based on that, a technology of commercial-scale extraction of rare earths from the plants was substantiated [40]. In China plant *S. plumbizincicola* was investigated as an accumulator of cadmium related with iron or manganese (hydro-oxide), which allowed using the plant in large-scale field phytoremediation [41]. It is also found that such a highly phytotoxic pollutant as Cr(VI) is absorbed by roots of plants *Arabidopsis thaliana*. The effect is enhanced in treatment of the contaminated soil with a high-affinity sulfate transporter [42]. In the Hunan province in China, in the area of uranium mines, plants *Z. pendula* and *Lolium perenne* increase efficiency of accumulation of U and Cd with introduction of chelates (oxalic and citric acids) in the contaminated soil [43, 44]. The studies also show that sowing of plants *Festuca arundinacea* with addition of saw dust ash and biochar mix in the contaminated soil reduced total Pb in it [45]. Chinese research on growing *Solanum nigrum* in pots proves the usability of the plant in phytoremediation of mining land through accumulation of Cd and Pb in soil introduced with citric acid and a new biodegradable chelate (polyglutamic acid) [46]. In China province of Guangdong, six prevailing weed plants were examined in terms of their ability to accumulate Cd and Pb in soil in the presence of rhizosphere bacteria generated by the root systems of the plants [47]. The same result of Cd and Pb accumulation was obtained in the investigation of plant *Paspalum conjugatum in the presence of bacteria Chloroflexi*, *Acidobacteria* and *Actinobacteria* [48].

In Chahar Gonbad copper province in Iran, out of 38 plants selected for the research, the most efficient accumulators of Cu, Fe and Zn were *Euphorbia gedrosiaca*, *Eremurus persicus*, *Scariola orientalis*, *Scorzonera intricata*, *Onobrychis Mill*, *Pteropyrum aucheri* and *Nepeta glomerulosa*. The selected plants accumulated toxic elements differently and were tolerable to soil pollution [49]. In India, in the areas of Jaipur, Kashipur, Jaspur and Bajpur, the studies of plant *H. annuus* enabled recommending it as a hyperaccumulator of Pb, Cd, Zn, Cu, Fe and As [50]. The studies also revealed that the other plant *S. Viarum* effectively accumulated Pb, Cd and Zn, which made it possible to recommend the plant for the phytoremediation of the polluted soil [51]. In mining and metallurgical region of Salem, Tamil Nadu in India, plant *C. zizanioides, in the presence of soil bacteria B. cereus, resistant to heavy metals, effectively accumulates* Cr, Cd, Zn, Pb and Mn, which allows using the plant in phytoremediation [52].

For the tropical countries in Southeast Asia (China, Vietnam and Thailand), it is recommended to use *Sorghum sudanense* for the contaminated soil cleanup through nickel accumulation in biomass. The effect of nickel accumulation in plants increased with addition of nitrilotriacetic acid and tea saponin in soil [53]. In the zinc-bearing ore mining province of Tak in Thailand, it was studied how organic additives influenced accumulation of Cd by plants *Acacia mangium*, *Jatropha curcas* and *Manihot esculenta*. Addition of bone dust, guano and leonardite improved growth both of *Acacia mangium* and *Manihot esculenta*, while adding solely bone dust appeared to be more effective for *Jatropha curcas* [54]. In Vietnam, within the limits of Ha Thuong, Hich Village and Trai Cai areas of complex of mining, the ability of plant *Lolium multiflorum* to accumulate As, Cd, Cu, Pb and Zn was analyzed. After addition of ethylenediaminetetraacetic acid and natural chelates (ethylenediamine-disuccinic acid and nitrilotriacetate) in soil, the biomass volume of the plant increased; the plant capability to accumulate Pb and Zn from polluted soil was proved [55].

Conclusions

The review of the applied research in the field of phytoremediation technologies in the mining industry worldwide has revealed the main trends of ecological activities and the problems to be handled in the nearest future. The new knowledge of phytoremediation enables ecologists to validate the use of plants in accumulation of toxic elements–pollutants of soil cover. In recent years, a new trend arises in phytoremediation, which is concerned with the analysis of aftereffects of contaminated soil application with organic substances with a view to stimulating accumulation of toxic compounds by plants. This is a basis of process control in the technologies of phytoremediation.

At the same time, in the authors' opinion, a global task is the analysis and synthesis of the world's knowledge of applied phytoremediation to compile a specialized atlas of charts. The atlas charts per each continent and each country should include: edaphic–climatic characteristics of mining and likely areas; species composition of plants capable to accumulate toxic elements, the known organic substances which, when introduced to contaminated soil, can decrease or increase capability of certain plants to accumulate toxic elements. The authors think that development and improvement of the chemical analysis, and understanding of the mechanisms of bioavailability inhibition of heavy metals, activation of their absorption, migration, accumulation and transportability by plants, etc. can allow applied ecologists to implement effectively technologies of phytoremediation on lands polluted by mining operations.

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