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Phytoextraction of rare earth elements

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Abstract. Rare earth elements (REE) are a group of 17 elements with similar physicochemical properties. Most of the world's REE extraction belongs to China. Due to the growing demand for REE and limited resources, the European Commission has identified REE as critical materials. On the other hand, little is known so far about the possible effects of long-term exposure of living organisms and the ecosystem to REE. Therefore, potential solutions for the recovery of distributed REE are being sought. Phytoextraction is a method that allows the recovery of elements from the environment. For this purpose, two strategies are generally used: the use of plants with the natural ability to accumulate REE (hyperaccumulators) and the support of the process through the use of chelators. Twenty two species have been identified as REE hyperaccumulators, e.g. *Phytolacca americana*, *Dicranopteris linearis*, *Blechnum niponicum* or *Carya tomentosa*. For the total REE, an accumulation limit of 100 mg kg^{-1} dry weight was established. Natural chelators are used as additives, e.g. humic acids or low molecular weight acids, as well as synthetic ones: EDTA or EGTA. In addition, the efficiency of the process is also influenced by other factors, such as the sorption capacity of the soil, the content of organic matter in the soil or soil pH. The aim of this article is to present the plant species useful in REE phytoextraction and the potential for enhancing the method with the use of chelators.

Keywords: rare earth elements, phytoextraction, hyperaccumulation, environmental remediation.

INTRODUCTION

REE (rare earth elements) are a group of 17 elements. This group includes 15 lanthanides from the third period of the periodic table of elements: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu) and 2 scandiums – yttrium (Y), scandium (Sc). These elements have similar physical and chemical properties (Całus-Moszko, Białecka, 2012). REE in the environment constitute a fairly coherent group in terms of their chemical and physical properties. The exception is the promethium consisting solely of short-lived radioactive isotopes formed during atomic reactions. Pm is easily degraded radioactively, its half-life is 2.62 years. Promethium does not occur in nature (Castor, Hedrick, 2006).

Due to the differences in atomic mass, REE are divided into: light rare earth elements (LREE) and heavy rare earth elements (HREE). The first group includes elements from La to Eu, and the second group from Gd to Lu. In the environment, REE occur mainly in the form of silicates and phosphates. The main minerals which include lanthanides are: monazite, bastnasite, and gadolinite (Całus-Moszko, Białecka, 2012). REE form a group of lithophilic elements concentrated in the earth's crust. They are part of very durable and weather-resistant minerals. They appear collectively because they are trivalent (the exception are cerium and europium, which may also appear in the form of Ce^{4+} and Eu^{2+}, respectively) and have similar ionic rays, thanks to which they can be mutually replaced in different crystal structures. Lanthanides with an even atomic number are more common in nature than those with an odd atomic number (Burchard-Dziubińska, 2014).

REE constitute the seventh most naturally occurring element in terms of fossil resources – their amount is comparable to gold or silver deposits. As a result, they are not as rare as their name suggests. The name refers rather to the fact that the REE deposits are very scattered and it is difficult to isolate them. The most abundant element is cerium being the 25th most abundant in the Earth's crust (Burchard-Dziubińska, 2014; Ramos et al., 2016). In 2019, REE global production was at the level of 210,000 tonnes. The largest share in the global production belonged to China (62%).

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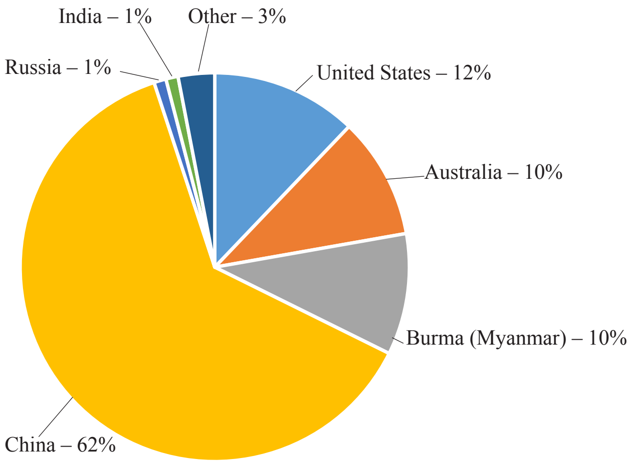

Figure 1. Distribution of REE production in 2019 (Garside, 2021).

Rare earth metals have special properties, making them desirable raw materials in many fields, including modern technologies, the so-called high-tech, industry, medicine and agriculture. First of all, they are used in renewable energy applications. They are used, among others, for the production of high-strength magnets applied in wind turbines, electronic equipment, electric vehicles and computers.

According to the European Commission, REE are considered critical materials due to the risks associated with their limited supply, as well as their importance for clean energy and advanced technologies. According to the latest research, neodymium (Nd), europium (Eu), dysprosium (Dy), terbium (Tb) and yttrium (Y) are the most critical of all REE due to their use in the production of magnets and lamp phosphors (Ji et al., 2020).

More than 200 minerals containing more than 0.01% of lanthanides are known. REE raw materials are usually obtained from such types of ores as: monazite (China, USA, Australia, India, Malaysia, Brazil, Thailand and Sri Lanka), bastnaesite (USA, China) and laterite ores. The above-mentioned raw materials are used to obtain REE mineral concentrates by means of flotation, magnetic and gravity enrichment. The selection of the appropriate method depends on the mineral-chemical composition, structure and texture of the raw material (Kwecko, 2016; Jarosiński, 2016).

The increased use of REE also leads to an increase in the amount of these elements in the environment. Exploration of REE causes their increased migration in the environment, which may disturb the balance of the ecosystem and negatively affect animals, plants and microorganisms. They are extracted to a large extent and this leads to increased volume of tailings or mining waste (Lima, Ottosen, 2021; Reisman et al., 2013). The increased risk of the environment contamination with REE may result from the extraction, processing as well as improper disposal of materials containing the metals in question. Therefore, substantial amounts of REE are dispersed near industrial waste disposal sites, within urban areas, wastelands where coal or metallurgical waste (slags and flotation waste) are accumulated. A high concentration of rare earth metals is also found in industrial wastewater and sludge. These sites and materials are considered as alternative sources for REE acquisition. Waste electrical and electronic equipment, phosphogypsum or fly ash from hard coal combustion can be a potential source of REE recovery (Całus-Moszko, Białecka, 2012; Moshin et al., 2022). To date, little research has been done on the behavior of REE in the environment. Some studies show a toxic effect of La, which can replace calcium (Ca) in some cell cycles due to its similarity to Ca ions. In studies conducted by Fan et al. (2004) it was proved that children exposed to REE have a lower IQ level compared to people in the reference group. The research also proved the negative influence of some REE on the nervous, circulatory and immune systems (Fan et al., 2004). In turn, in the experiment conducted on grasshoppers, their consumption of biomass with a higher Ce content caused muscle paralysis within four days after ingestion (Allison et al., 2015; Chen et al., 2020). However, in general there is not much evidence of a negative effect of REE to organisms, especially in long-term studies.

The aim of the study is to discuss a nature-based method of REE recovery through phytoextraction that could potentially lead to clean up of the environment from the excess of REE. The review takes into account plant species that can accumulate the discussed elements, as well as factors that affect the phytoextraction process.

PHYTOEXTRACTION PRINCIPLES

The term phytoextraction refers to a technique that uses selected plant species to recover elements from the soil that are accumulated in the above-ground parts of plants. The purpose of the method is to reduce the level of elements in the soil as well as to aquire them from the environment in plant biomass as a secondary source of these elements (Xing, 2006).

The initial stage of phytoextraction covers selection of the site where the given metals occur in elevated concentrations. Such areas include naturally enriched or contaminated soils, such as mining or industrial areas. Next step is a selection of appropriate plant species and possible soil additives that would optimise the uptake of the elements from the substrate or the overall growth of the plant. Examples of such additives include phytohormones, fertilizers and exogenous organic matter. The final stage is harvesting the crop. Biomass can be reduced by composting or thermal treatments or used for the recovery of certain elements (Grobelak et al., 2010; Krzciuk, 2019). From the physiological point of view, the process of taking an element from the soil by a plant includes the following stages: solubilization of metal from the soil matrix, acidification of the rhizosphere and secretion of ligands, metal absorption by roots and transport to shoots, distribution between tissues and sequestration. REE in plants can be stored in various tissues, such as: mesophyll, epidermis or xylem, in places where the elements do not have a toxic effect on important cellular processes. In contrast, sequestration, the last step leading to accumulation, takes place in the vacuole, where the metal or its ligand complex is transported across the vacuolar membrane (Opare et al., 2021; Shan et al., 2003; El-Remady, 2010).

Two approaches are used in the phytoextraction process: the use of plants that have the natural ability to accumulate metals in greater amounts (hyperaccumulators) and those that accumulate REE in small amounts. The second approach uses application of chemicals called chelators as soil amendments. Hyperaccumulators are plants that are able to accumulate large amounts of metals in their organs without suffering a toxic effect of the element accumulation. Currently, threshold values in mg kg^{-1} dry weight have been proposed for some elements as levels qualifying plants as hyperaccumulators: for Se, Cd, Tl are 100 mg kg^{-1}; for Cu, Co, Cr it is 300 mg kg^{-1}; for Zn it is 3000 mg kg^{-1}; for Mn 10000 mg kg^{-1} (van der Ent et al., 2013). In general plants accumulate, among others, such metals as Fe, Mn, Zn, Cd, Cu, Mg and Mo (Bhargava et al., 2012). In order to qualify for this process, plant species should have an abundant root system, fast growth rate, tolerance to high levels of metal in the substrate, and the ability to accumulate high levels of metal in its aboveground parts (Garbisu, Alkorta, 2001; Xing, 2006). Hyperaccumulators are able to store 10-500 times higher levels of metals than crops. An example of a Zn and Cd hyperaccumulator is *Thlaspi caerulescens*, which is able to accumulate and tolerate 10,000 mg kg^{-1} Zn and 100 mg kg^{-1} Cd in the dry weight of shoots without showing any symptoms of toxicity (Escarre et al., 2011).

Two strategies for extracting metals by plants are used: continuous phytoextraction and induced, chemically assisted phytoextraction (Tahmasbian, Safari Sinegani, 2016). The first type of the process relies on the natural ability of certain plant species to accumulate and resist high concentrations of metals. On the other hand, the second approach uses chelating compounds responsible for the increased accumulation of metals (Krzciuk, 2015). Table 1 shows the differences between the two phytoextraction methods.

FACTORS INFLUENCING REE HYPERACCUMULATION

Currently, more than 400 plant species classified as natural metal hyperaccumulators have been identified, but the list of species is still being developed. Twenty two species have been identified as REE hyperaccumulators. The species recognized as REE hyperaccumulators represent five families: Phytolaccaceae (e.g. *Phytolacca americana, P. icosandra*), Gleicheniaceae (e.g. *Dicranopteris linearis*), Blechnaceae (e.g. *Blechnum niponicum, Woodwardia japonica*), Juglandaceae (e.g. *Carya cathayensis, C. glabra, C. tomentosa*), Thelypteridaceae (e.g. *Pronephrium simplex, P. triphyllum*) (Krzciuk, 2015; Jalali, Lebeau, 2021). For the total REE, an accumulation limit of 100 mg kg^{-1} dry weight was established (van der Ent et al., 2021).

The following soil factors may affect hyperaccumulation: cation exchange capacity, organic matter content, pH, metal content in the substrate. Only limited part of the element pool in soil is bioavailable to plants. The rest is mostly in insoluble forms, making them inaccessible for adsorption by the plant roots. It has been proved that REE are more mobile in solutions rich in F^-, Cl^-, HCO_3^-, CO_3^{2-}, HPO_4^{2-}, PO_4^{3-} ions. The isomorphic replacement of calcium with REE is due to their similar ion radius, making carbonates the preferred form of REE in soils. However, in order to increase the biomass of plants, it is important not only to maintain the optimal pH, but also properly fertilize, which supports growth of plants. Examples of such fertilizers are nitrogen and potassium fertilizers, which when added to the soil lower the pH, increasing the mobility of most trace elements. On the other hand, they contribute to plant growth, as they contain important biogenic elements. It has been proven that the addition of such substances increases the accumulation of elements (Lihong et al., 1999; Balaram, 2019). Phosphorus fertilizers used in agriculture might contain REE at levels two orders of magnitude higher than in uncontaminated agricultural soils. Turra et al. (2019) conducted a greenhouse experiment on Rangpur lime (*Cit-*

Table 1. Differences in the application of two phytoextraction techniques (Nascimento, Xing, 2006).

Chemically assisted phytoextraction	Natural phytoextraction
Plants need the right conditions to accumulate metals	Plants naturally hyperaccumulate metals
Fast growth, high biomass	Slow growth, low biomass growth
Strengthening the uptake of metals by the addition of synthetic chelators or organic acids	Natural metal extraction capacity
Low level of metal tolerance – can be toxic to the plant	High level of tolerance, possibility of accumulation of high concentrations of metals without toxic effects on plants
Risk of release of metal chelates into the environment	No risk to the environment

rus limonia Osbeck) plants using superphosphate fertilizer. The concentration of REE in the substrate increased after the application of the fertilizer. In the examined citrus plants, a higher concentration of REE was recorded in the leaves than in the branches. The substrate-plant transfer rates for La, Ce, Sm and Sc ranged from 0.0002 to 0.0047. The highest substrate-leaf transfer rate was observed for La (0.0047) (Turra et al., 2019). In terms of binding with organic matter, REE behave in soils similarly to other trace elements. Organic matter is fundamental for the adsorption of REE as it provides negative charges in the solid phase of soils (Lihong et al., 1999; Balaram, 2019).

Soil pH has a significant impact on the growth and development of hyperaccumulating plants. It strongly influences the availability of nutrients and elements of interest to plants, as well as the toxicity of metals in the substrate. Typically, the concentration of metals in the solution is increased by lowering the pH value. A drop in pH causes a large amount of metal ions to be desorbed from the surface of colloids and clay particles, from where it gets into the soil solution. Hence, lowering the pH may disturb the balance of metal ions precipitation and positively affect their release into the soil solution. The optimal value of the availability of macronutrients for plants is in the range of pH 6 to 7 (Sheoran et al., 2016; Corzo Remigio et al., 2020).

Hyperaccumulating plants are classified using the BF (bioaccumulation factor) and the TF (translocation factor). The value of both factors for the plants in question should be greater than 1. The BF is the efficiency of accumulation and is defined as the ratio of an element concentration in the above-ground parts of the plant to its amount in the soil. The TF describes the efficiency of metal movement and it is the ratio between the concentration of metals in plant shoots to the concentration of metals in the roots (Szarek-Łukaszewska, 2014; Krzciuk, 2015).

There are two pathways of metal transport in hyperaccumulators: apoplastic and symplastic. The apoplastic transport process has been identified in most plant species. However, REE absorption encounters the first apoplastic barrier in the roots, which makes it difficult to transport the elements to xylem and then translocate to other plant organs. As a result, the content of elements in the organs is as follows: roots> stems> leaves> flowers> fruit (Ramos et al., 2016; Brioschi, 2013). For example, the accumulation of Zn, Cd and Ni occurs mainly in the cell walls located outside the plasma membrane of the epidermis, the endodermal cortex to the Casparian band, while not occurring in the stele (Shan et al., 2003).

CHELATE-ASSISTED PHYTOEXTRACTION

In order to make the phytoextraction process more efficient, certain compounds assisting the uptake of metals from the environment have been tested. The example is a group of compounds called chelators.

Organic and inorganic ligands play an important role in root absorption of various elements. These are synthetic APCA (aminopolycarboxylic acids): EDTA (ethylenediaminetetraacetic acid), ethylene-bis [oxyethylene trinitrilo] tetraacetic acid (EGTA), ethylene-diamino-N, N 0 bis (o-hydroxyphenyl) acetic acid (EDDHA), N-(2-hydroxyethyl) iminodiacetic acid (HEIDA), while natural APCAs are: ethylenediamine disuccinate (EDDS), nitrilotriacetic acid (NTA), natural low molecular weight organic acids (NLMWOA), humic substances (HS). Metals complexed with the ligands mentioned above are more accessible to plant roots (Salt et al., 1995; Jabeen et al., 2009). Table 2 shows examples of chelating compounds and their effect on the mobilization and plant uptake of trace elements.

Table 2. Chelating compounds and their influence on the mobilization and uptake of metals.

Chelator	Amount added [mmol kg^{-1}]	Metal	Increase in metal absorption compared to control	Plant species	Side effects	Reference
NTA	2	Pb	23.8%	Fern *(Athyrium wardii)*	No side effects	Yu et al. (2020)
EDTA	5	Cu	12-times	Corn (*Zea mays*)	Plant growth down to 60% compared to the control	Luo et al. (2005)
EDDS	2.5	Co	5-times	Chinese milk vetch (*Astragalus sinicus* L.)	No side effects	Chen et al. (2019)
Citric acid	20	Ni	55%	*Odontarrhena muralis*	Visual symptoms of toxicity: chlorosis and necrosis on leaves	do Nascimento et al. (2020)
Citric acid	3	Pb	2-times	Indian mustard (*Brassica juncea*)	No evidence of toxicity	Wu et al. (2013)

In conclusion from the attached table, the addition of chelators can increase the absorption of metals by up to 12-times compared to the control, as in the case of *Zea mays* after adding EDTA to the soil.

Synthetic chelators are characterized by high toxicity and low biodegradability. The risk of using the chelators to optimize phytoextraction may be related to the potential of their release into the environment. The use of synthetic chelators should be limited to controlled conditions, e.g. small soil volumes or constructed systems, in order to avoid the release of chelators to groundwater (Moschner et al., 2020). For example, the use of EDTA in Pb phytoextraction raises concerns related to the long term retention of the chelator in the soil profile and its resistance to microbial decomposition (Hart et al., 2022).

FEASIBILITY OF REE PHYTOEXTRACTION

In low doses, REE can have a positive effect on the development of plants: they stimulate seed germination, the growth of roots, leaves or stems. However, the improvement of plant growth is limited only to certain stages or substrate conditions (Zhang et al., 2013; Thomas et al., 2014). It has been proved that a high concentration of REE in the substrate may negatively affect the growth of the plants. As a result, it may not be possible to recover satisfactory amount of REE along with the biomass. A substantial knowledge gap concerning feasibility of REE phytoextraction is related to the fact that most of the research on the effects of these elements on plants has been carried out under hydroponic conditions (Thomas et al., 2014).

As mentioned previously, REE are not essential for plants, but plants accumulate these elements from the soil or substrate through their roots or also through leaves from dust deposition, this is mainly the case in mining and urban areas. In case of accumulation by means of roots, the limitation is related to root system development. Metals beyond the root reach cannot be taken (Tyler, 2004; Khan et al., 2016).

Another limitation of the phytoextraction process is that the phytoextraction efficiency is closely related to the plant growth – the extraction rate is in general proportional to the plant biomass and the concentration of an element of interest. Therefore unassisted phytoextraction process is very slow (Bhargava et al., 2012). For phytoextraction to be considered economically viable, it is necessary that the bioconcentration factor of the metals provided by the plant species concerned is 20 and the biomass production is at least 10 tonnes per hectare (Peuke, Rennenberg, 2005; Bhargava et al., 2012). This makes the phytoextraction efficiency of REE using regular crops generally not economically justified. Therefore, one of the possible solutions is to use plants that occur naturally in areas contaminated with rare earth metals. These species are naturally resistant to high concentrations of potentially toxic elements without suffering toxicity. Some of them also exhibit natural capacity for enhanced metal uptake. An example is the *Phytolacca americana*, which occurs naturally in the United States and can reach up to 3 meters in height (Grosjean et al., 2019). The use of native species in phytoextraction may also prevent the introduction of invasive plant species into the ecosystem (Zhou et al., 2015). Examples of species of plants naturally accumulating REE are presented in Table 3.

An effective solution is to support the phytoextraction process by adding soil amendments that increase REE solubility (e.g. chelators) or improving soil conditions to stimulate better plant growth. In the studies by Xueyuan et al. (2001), wheat seedlings were used for the purpose of REE absorption. The experiment involved the addition of humic acid (HA). It was shown that lower concentrations of HA <0.2 g kg^{-1} favored the accumulation of rare earth metals in the roots, but concentrations higher than 0.2 g kg^{-1} decreased the concentration of REE (Xueyuan et al., 2001).

Plants can secrete natural metal chelating molecules into the rhizosphere. Its goal is to mobilize soil-bound metals. The key root exudates are low molecular weight organic acids (LMWOA). These are oxalic, succinic, tartaric, formic, malic, acetic, butyric, lactic, fumaric, maleic, and citric acids (Sokolova, 2020). Due to their chelating or metal complexing properties, they can influence the solubility of elements in the soil and their uptake by plants. The highest association constant at pH approx. 7.5 for metal complex formation has the protein amino-acid histidine (Shan et al., 2003.). *Dicranopteris dichotoma*, a fern growing in acidic soils in southern China, hyperaccumulates several LREE such as La, Ce, Nd and Pr to around 0.7% of the dry leaf weight. In the experiment of Shan et al. (2003) the addition of malic acid, histidine and citric acid was used to stimulate REE uptake from the substrate. For example, adding histidine to the soil in which ferns grew for 60 days caused an increase in LREE in their leaves by 21–34%, while in the control leaves only by 6–10% (Shan et al., 2003). In the studies of Khan et al. (2016), attention was focused on plants belonging to the Cyperaceae, Gleicheniaceae and Melastomaceae families. Research has shown that *Dicranopteris linearis* and *Cyperus rotundus* L. can be included as REE hyperaccumulators. The highest concentrations of Ce (1482.60 µg g^{-1}) and La (1305.07 µg g^{-1}) were reported for *D. lineraris*. *C. rotundus* L. accumulated 568.90 µg of La g^{-1} (Khan et al., 2016).

Wu et al. (2013) reported that the absorption of La by tomato (*Lycopersicon esculentum* Mill) by the whole plant biomass, increased after the addition of aspartic acid, asparagine, histidine and glutamic acid, compared to the control. The concentration of La in tomato after its treatments with aspartic acid and asparagine increased to 449 µg g^{-1} (Wu et al., 2013).

Table 3. Natural REE hyperaccumulators.

Rare earth elements	Concentration in plants [mg kg^{-1}]	Plant species	Location	Reference
LREE	732.97 (leaves) 581.30 (roots)	*Dicranopteris dichotoma*	mining area (Malaysia)	Khan et al. (2016)
HREE	27.71 (leaves) 77.70 (roots)			
	BF – 143.29			
LREE	240.65 (roots)	*Dicranopteris linearis*	mining area (Malaysia)	Khan et al. (2016)
HREE	9.97 (roots)			
	BF – 219.16			
LREE	515.08 (leaves) 475.78 (roots)	*Cyperus rotundus*	area by the river (Malaysia)	Khan et al. (2016)
HREE	78.33 (leaves) 137.82 (roots)			
	BF – 387.11			
REE	514 (leaves) BF 0.22 – 1.51	*Phytolacca americana*	mining area (China)	Liu et al. (2021)
LREE	1040 (leaves) BF – 0.37	*Phytolacca americana*	mining area (China)	Yuan et al. (2018)
REE	520.78 (shoots) 33.94 (roots) BF>100	*Atriplex leucoclada* Boiss.	mining area (Iran)	Tabasi et al. (2018)
REE	13 (leaves)	*Phytolacca icosandra*	-	Grosjeana et al. (2019)
La Ce	144 (leaves) 325 (leaves)	*Carya tomentosa*	natural soil (United States)	Wood, Grauke (2011)
La Ce	108 (leaves) 276 (leaves)	*Carya cordiformis*	natural soil (United States)	Wood, Grauke (2011)
REE	177 (roots)	*Cistus monspeliensis*	mining area (Portugal)	Durães et al. (2014)

BF – bioaccumulation factor

Table 4. Efficiency of REE phytoextraction supported by chelators.

Rare earth elements	Increase in REE accumulation compared to control	Species	Basis	Addition/chelator	Reference
REE	3.5 times	*Phytolacca americana*	mining area (China)	biochar (addition of fir sawdust)	Liu et al. (2020)
La	4-57%	*Triticum aestivum* L.	hydroponic system	acetic acid, malic acid	Wang et al. (2004)
La, Ce, Pr, Nd	21-78%	*Dicranopteris dichotoma*	REE ore deposit (China)	histidic acid, malic acid, citric acid	Shan et al. (2003)
La, Nd Gd, Er	20 times 10 times	*Phalaris arundinacea*	clayey silt (Germany)	citric acid	Wiche et al. (2017)
REE	46%	*Zea mays*	greenhouse experience	cow dung	Okoroafor et al. (2022)

Soil amendments may promote the recovery of REE from soil. The influence of pig manure and biochar with the addition of fir sawdust on phytoextraction of REE with *Phytolacca americana* was investigated by Liu et al. (2020). It was concluded that soil additives improved the physicochemical properties of the soil. However, a significant effect (the sums of REE harvested was 3.56 times higher compared to the control) was only achieved after the addition of low dose of biochar (1%). In the case of higher concentrations, soil pH and the amount of organic carbon and nutrients increased, which in consequence reduced the bioavailability of REE in the medium (Liu et al., 2020). Table 4 shows efficiency of REE phytoextraction supported by chelators.

Another strategy used in phytoextraction might be based on interspecific interactions between plants. For example, in the studies by Wiche et al. (2016), REE uptake was tested using the interspecific interaction between barley (*Hordeum vulgare* L., cv. Modena) and white lupine (*Lupinus albus* L., cv. Foedora) under field conditions. It was shown that the concentrations of REE in the shoots of white lupine monocultures were about two times higher than in barley. Furthermore, a significant increase in La, Nd, Sm, Gd, Y was recorded in barley shoots in the variant consisting of intercropping with lupine. Such research proves that the proper selection of plants can contribute to the increased absorption of REE from the substrate. However, the appropriate ratio of the tested plants in the intercropping should be selected for the process to be efficient (Wiche et al., 2016).

CONCLUSIONS

REE can pose a threat to the natural ecosystem. Increased demand for technologies in which REE are increasingly used causes their release into the environment. Therefore, methods should be sought to enable the rehabilitation of contaminated areas. Phytoextraction is a method that uses plants that can accumulate elements without having toxic effects on their growth. In general two phytoextraction strategies are used. The first one involves plants naturally accumulating metals, i.e. hyperaccumulators, while the second one involves the addition of chelators to facilitate the absorption of elements from the substrate. The advantages of phytoextraction include the fact that it is in general safe for the environment, cost-effective and the produced biomass can be subjected to further stages of REE recovery. However, REE phytoextraction has some limitations: so far there are few plant species capable of accumulating REE, the concentrations of REE in plants are not satisfactorily high which does not make the process of REE extraction from the biomass economically viable. It is clear that more research is needed on optimalisation of REE phytoextraction. This shall involve further selection of plants, nature based solutions enhancing accumulation of REE in plant shoots and using substrates containing rich-REE waste instead of soil for plant-based recovery of these elements.

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