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Phytoextraction of Lead: Its Feasibility, Constraints and Concerns

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

Aims: With lead being one of the most common soil contaminants and phytoextraction has been reported as a prospective method for remediation of lead-contaminated soil, this review aims to examine the feasibility of lead phytoextraction as well as its constraints and concerns.

Study Design: This is a literature review.

Methodology: Peer-reviewed papers were sourced from scholarly databases. The papers included in the review were mainly those about phytoextraction of lead, particularly with the shoot, soil and root concentrations of lead mentioned as well as the bioconcentration and translocation factors stated. Besides, papers discussing the limits, for instance, the duration of lead phytoextraction, and concerns of the approach were also included.

Results: This review found only 11 plants have been reported to accumulate lead in shoots at nominal threshold of near or above 1,000 mg Pb/kg dry weight and in certain cases, soil amendment was required to achieve this. Only two of the plants had bioconcentration factor > 1 and another two had translocation factor > 1. None of the plants fulfilled all three criteria of a successful hyperaccumulator, indicating the constraints and a lack of feasibility of lead phytoextraction. Besides, lead phytoextraction has been predicted to require significant amount of time, hence increasing the risk of exposure to lead.

Conclusion: This review highlights that lead phytoextraction may not be feasible for the remediation

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of lead-contaminated soil. It recommends phytostabilization as a more viable alternative to immobilize lead in rhizosphere and reduce lead exposure.

Keywords: Bioaccumulation; lead; phytoextraction; phytostabilization; safety; translocation.

1. INTRODUCTION

Anthropogenic activities have left behind a multitude of contaminants in the environment with soil included [1]. The emergence of phytoremediation which involves the use of plants to remove contaminants from soil and other components of the environment has provided a cost-effective and uncomplicated environmental remediation option though it often requires longer time to reduce contaminants to acceptable levels [2]. To enhance the effectiveness of phytoremediation, application of microbes and modification of abiotic conditions could be employed concurrently. These could enhance the mechanisms of phytoremediation which typically comprises rhizofiltration, phytostabilization and phytodegradation occurring in the root zone as well as phytovolatilization and phytoextraction occurring aboveground [3].

Rhizofiltration involves the removal of contaminants through absorption or adsorption by roots, usually in an aquatic environment to clean up water [4,5]. Phytostabilization immobilizes contaminants and it generally occurs near the root zone where roots facilitate the binding of pollutants to soil or secrete substances that convert pollutants to a less toxic form [4,6]. Phytodegradation, however, is the degradation of soil contaminants by the microorganisms attached to plant roots or by the enzymes secreted by the roots [7]. Aboveground, phytovolatilization releases contaminants absorbed from soil or water into the air and in some instances, the contaminants would have been transformed into more volatile or less polluting variants. In phytoextraction, pollutants are taken up from soil or water by roots and transported to the aboveground biomass [8]. This is the predominant mechanism of hyperaccumulators for removing environmental contaminants.

Lead is a common soil pollutant. It is naturally occurring at a concentration of approximately 20 mg/kg though its concentration varies in different formation for instance 2.4 mg/kg in basalt and 30 mg/kg in granite [9]. Lead mining has a long history and was initially associated with silver extraction from lead-silver alloys [10]. In 2019, the global mine production of lead totalled 4.5 million tonnes with China leading lead production with a share of 46.7%. In terms of refined production of lead, the amount in 2019 was 11.3 million tonnes and the largest share also came from China (42.7%), followed by United States (9.8%) and South Korea (6.7%) [11]. With high density, low melting point and malleability, lead has found a wide range of uses, for instance in pipes, printing presses, batteries and paints [12]. While the uses of lead have been increasingly regulated due to health and environmental concerns, the remnant lead in the environment, particularly in soil remains a major public health threat. It has been reported that surface soils globally especially in urban areas still contain high levels of lead [13,14] and the lead contents could be linked to point sources such as lead mining and smelting or non-point sources such as incineration and wind-blown particles [15].

Numerous approaches have been employed to modify the speciation, mobility and bioavailability of lead to render it less harmful [16]. These include the application of biochar [17], biosolids [18] and zero-valent iron nanoparticles [19]. Nonetheless, such modifications usually incur high cost and are reversible in certain cases [20]. Excavation of lead contaminated soil for containment or treatment is the preferred option of many regulators but it is cost-prohibitive and logistically challenging. Besides, it diverts the risk of lead contamination elsewhere [21]. Covering contaminated soil with new soil, geotextile and mulches are significantly less costly and could be effective in limiting exposure provided that maintenance of the coverings is periodically conducted [22,23]. Despite, the contaminated soil is not remediated. Phytoremediation, therefore, receives the attention as a low-cost option to remove lead from soil.

Lead is usually strongly bound to soil particles and immobilized unless it is desorbed from the binding sites and this process is very slow. After desorption, lead needs to move through soil solution before adsorbing to or precipitating at new binding sites [16]. Binding sites with high concentrations of organic matter and clays having reactive surfaces facilitate accumulation of lead [24]. Solubilized or mobilized lead can be absorbed by roots in ionic or chelated form, actively or passively while lead not absorbed by plants will eventually find its way to the groundwater [25]. With the concern of lead in the environment and the potential of phytoremediation to remove lead from soil, this review serves two aims 1) It examines the feasibility of phytoextraction of lead from soil with the criteria of good hyperaccumulation, and 2) It highlights the constraints and concerns of lead phytoextraction.

2. METHODOLOGY

This review retrieved peer-reviewed scholarly articles from databases comprising Google Scholar, Web of Science, ProQuest and Scopus with keywords such as lead, phytoremediation, phytoextraction, efficiency, bioaccumulation factor, translocation factor and hyperaccumulation [26,27]. Papers concerning phytoremediation in general or not focusing on lead were excluded. The papers included were mainly those about phytoextraction of lead, particularly with the shoot, soil and root concentrations of lead mentioned as well as the bioconcentration and translocation factors stated. Besides, papers discussing the limits, for instance, the duration of lead phytoextraction, and concerns of the approach were also included.

3. RESULTS AND DISCUSSION

3.1 Criteria of Lead Hyperaccumulation

Lead is commonly extracted from soil by hyperaccumulators. Hyperaccumulator was initially coined for plants which could concentrate > 1,000 mg of Ni per kg dry weight. It was subsequently extended to other metals and metalloids. To qualify as a hyperaccumulator, a plant must be able to accumulate a minimum of 100 mg/kg Cd, Se and Tl, 300 mg/kg Cu, Co and Cr, 1,000 mg/kg Ni, As and Pb, 10,000 mg/kg Mn, or 3,000 mg/kg Zn, without showing signs of phytotoxicity [28,29]. A hyperaccumulator could normally concentrate a contaminant to a level 10 to 1,000 times higher than that by a non-hyperaccumulator under natural conditions without soil and nutrients amendment [30]. A hyperaccumulator typically has a bioconcentration factor > 1, a translocation factor > 1 and high tolerance to a metal due to certain biochemical processes [30]. The reason that natural condition has been emphasized as a criterion of hyperaccumulators is that there were instances where addition of chelating agents and nutrient solutions significantly enhanced lead uptake and translocation in *Brassica juncea* (Indian mustard) and *Brassica napus* (canola) through mobilizing lead in soil water and weakening root membranes [31,25]. Concurrently, such lead mobilization also caused more leaching into groundwater and this is impractical for remediation [32]. It is therefore crucial to examine if the effectiveness of lead phytoremediation reported in the literature is not due to the effect of chelating agents such as EDTA. A successful lead hyperaccumulator is one with shoot concentration having a nominal threshold of 1,000 mg Pb/kg dry weight, a bioconcentration factor (BCF) > 1 and a translocation factor (TF) > 1 [30]. While the definitions of bioconcentration and translocation factors are inconsistent in literature, bioconcentration factor in this review refers to the ratio of shoot concentration over soil concentration ([shoot]/[soil]) while translocation factor is the ratio of shoot concentration over root concentration ([shoot]/[root]) [30]. Both are indicators of phytoextraction.

3.2 Feasibility of Lead Phytoextraction

Hyperaccumulation of lead is not common as lead has limited phytoavailability due to its immobilization in soil. This review found only 10 plant species containing > 1,000 mg Pb/ kg dry weight and 1 species near 1,000 mg Pb/kg dry weight (Table 1). The studies reporting high nominal threshold of lead were conducted with highly contaminated soil with lead concentrations ranging from 1,422 – 22,234 mg/kg. In addition, the uptake of lead by plants correlates with its bioavailability in soil and it is likely that the conditions in these studies favored high phytoavailability of lead. In addition, the fact that some of the studies were conducted in field settings where wind and rain might cause resuspension of contaminated soil particles and their subsequent deposition on plant surfaces could contribute to elevated lead concentrations in plant tissues. The soil pH in these studies varied with four studies reported acidic soil pH of 4.7 – 5.4 while others reported alkaline soil pH of 7.3 – 8. While low pH favors solubilization of lead, the studies did not demonstrate a regular variation of lead uptake with pH. A reason is that soluble complexes formed a higher pH such as those between lead and soil organic matter could also increase phytoavailability of lead [33].

Table 1. Plant with Significant Ability to Accumulate Lead

Plant	Scientific Name	Pb in Shoot (mg/kg dw)	Pb in Soil (mg/kg)	BCF	TF	Soil pH	Ref.
Arrowhead violet	*Viola baoshanensis*	1,902	9,689	0.20	1.48	NA	[34]
Burma padauk*	*Pterocarpus macrocarpus*	1,132	9,850 – 22,234	0.11 max	0.08	7.4	[35]
Geranium	*Pelargonium capitatum* cv. 'Atomic'	1,107	1,830	0.60	NA	8.0	[36]
Geranium	*Pelargonium capitatum* cv. 'Attar'	1,467	1,830	0.80	NA	8.0	[36]
Geranium	*Pelargonium capitatum* cv. 'Clorinda'	1,182	1,830	0.65	NA	8.0	[36]
Groundsel	*Senecio* sp.	4,253	13,105	0.32	9.00	7.3	[37]
Norway spruce	*Picea abies*	3,000	1,422	2.11	NA	5.3	[38]
Scotch pine	*Pinus silvestris*	2,500	1,422	1.75	NA	5.3	[38)]
Ryegrass	*Lolium perenne* cv. 'Cadix'	2,000	20,703	0.10	NA	5.4	[39]
Thai crape myrtle*	*Lagerstroemia floribunda*	1,338	9,850 – 22,234	0.14 max	0.10	7.4	[35]
Vetiver*	*Vetiveria zizanoides*	934	22,234	0.04	NA	4.7	[40]

**Subject to soil amendment*

The contents of soil organic matter are known to affect lead mobility. Organic matter could increase lead mobility by forming mobile chelates or decrease mobilization of lead through binding and precipitation [24]. The studies in Table 1 demonstrating lead hyperaccumulation had generally low soil organic matter between 0.12% to 5%, in contrast to a typical 5% for field soils probably due to a lack of organic matter replenishment as the soils were subject to anthropogenic disturbance [41]. Soil texture also contributes to lead uptake by plant. Sandy soils might result in higher lead mobility due to the presence of macropores and low cation exchange capacity [41]. Silt loam soils, however, could bind lead to a greater extent due to the presence of clay [42]. The clay profile of the 11 cases of hyperaccumulation reported was not provided to allow an evaluation of how clay profile affected the efficiency of hyperaccumulation.

In relation to BCF and TF > 1 defined by van der Ent et al. for hyperaccumulators, only Norway spruce and Scotch pine meet the requirement for BCF while only arrowhead violet and groundsel meet the requirement for TF. Nonetheless, only few studies reported the TF values or allowed the values to be calculated and it cannot be ruled out that other plants whose TF values are not available are not able to meet the defined TF requirement. With the current available data, none of the plants in Table 1 seem to be able to qualify as successful hyperaccumulators defined in Section 3.1, though arrowhead violet, groundsel, Norway spruce and Scotch pine meet two of the three criteria of a successful hyperaccumulator.

Therefore, an obvious limitation in phytoextraction of lead is in the selection of plants which could meet all the requirements of a hyperaccumulator and in many instances, soil modification may be required. Some of the studies in Table 1, for instance, those involving Thai crape myrtle and vetiver were subject to soil amendment through the application of fertilizers. The use of chemical fertilizers would increase the cost of phytoremediation, hence reducing its cost-effectiveness. Where fertilizer application is required, organic fertilizers such as compost and biosolids could be considered. There are multiple studies conducted on chelate-assisted phytoextraction, for instance, it was found that Pb accumulation by cattail (*Typha latifolia*) was greatly enhanced with TF ≥ 1 and BCF ≥ 2 when subjected to citric acid amendment under hydroponic condition. However, such amendment brings in additional cost consideration and the study setting has limited relevance to soil phytoremediation [43]. While chelating agents such as citric acid and EDTA could increase the mobilization of lead in soil, thus enhancing uptake by plants, there are concerns of increased leaching of lead to groundwater and contamination of ecosystems which would add to the cost of environmental damage [44]. Besides, EDTA is expensive and it counteracts the cost advantage offered by phytoremediation [45].

3.3 Microbial Communities Associated with Plants

Studies have pointed to the toxic effects of lead and other heavy metals on microbial biomass, activity and diversity [46,47]. Different bacteria demonstrated different resistance to lead. For instance, *Proteobacteria*, *Verrucomicrobia*, *Firmicutes* and *Actinobacteria* were found to be highly sensitive to lead and other heavy metals [47]. Despite, Xu et al. also found certain members of *Proteobacteria* and *Verrucomicrobia* to be lead- and zinc-tolerant [48]. While the bacterial communities are affected by lead contamination, they may also have a role to play in lead phytoremediation. Sessitsch et al. found microbial communities to modify root absorption through increasing root length and hairs or bioavailability of metals [49]. Mycorrhiza growing on roots has also been reported to increase lead uptake and transport to shoot [40,50]. However, in some instances, mycorrhiza caused immobilization of lead in soil but there could be other confounding factors at play that require further investigation [51,52]. There is a need to further understand how microbial interactions affect lead phytoavailability.

3.4 Duration and Safety of Lead Phytoextraction

Uptake of lead by a successful hyperaccumulator which fulfils the criteria stated in Section 3.1 may occur over a long duration. *Pelargonium attar* with the ability to hyperaccumulate lead was estimated to take at least 151 years to phytoremediate a calcareous soil with a pH of 8 contaminated with 1,830 mg Pb/kg. In acidic soil with pH of 6 contaminated with 39,250 mg Pb/kg, the phytoremediation would take 914 years [36]. The estimation was conducted using a linear model which correlates quantity of lead extracted per hectare per year to dry weight of plant biomass per plant, density of plants per hectare, total lead concentration in per kg of shoot dry weight, as well as the number of crops per year. Van Nevel et al., however, was of the opinion that a logarithmic removal model with successive cropping could be more realistic for metal as linear model tends to overestimate remediation capacity. The reason is that the available metals for phytoextraction are likely to decrease with time, in addition to other confounding factors such as depleting nutrients in soil [53]. To date, it is still a challenge to derive a reliable mechanistic model to satisfactorily estimate the changes of metals in different compartments of soil with time and the resultant changes in plant uptake [54].

The slow phytoextraction of lead was also reported by Porebska and Ostrowska that each cropping cycle only removes less than 1% of lead in soil and it would take years to attain significant lead removal [55]. It is therefore crucial to test how different stages of plant growth and agricultural practices could optimize removal of heavy metals. With optimization, significant removal of lead from soil could still take decades [55]. Therefore, the long duration required for phytoremediation of lead-contaminated soil and the need of manpower for maintenance of plants and monitoring of phytoremediation give rise to safety concerns in the application of lead phytoextraction by hyperaccumulators. Human exposure to lead over the duration of phytoremediation remains a possibility especially on contaminated sites with high lead concentrations and phytoextraction as a slow process prolongs such exposure [56,57]. Besides, translocation of lead to aboveground biomass during phytoextraction may introduce lead into food chain, as well as cause accumulation of lead in topsoil and lead exposure due to dispersed plant materials contaminated with lead. It, therefore, warrants, special attention in the selection of plants for phytoextraction and edible crops are to be avoided [45].

4. CONCLUSION

Phytoextraction of lead has been perceived as a prospective method to remediate lead contaminated soil in many studies. However, its practical feasibility has not been adequately assessed. To qualify as a successful hyperaccumulator for lead phytoextraction, three criteria have been proposed, namely, a nominal threshold of 1,000 mg Pb/ kg dry weight of shoot, a BCF > 1 and a TF > 1. This review shows that, based on the available data, none of the plants included in the review, meet all the requirements. Besides, phytoextraction has been demonstrated with modelling to be time-consuming and this significantly increases exposure of human as well as other organisms to lead. Soil amendment with chelating agents is cost-prohibitive and imposes risk of leaching, hence groundwater contamination. Therefore, phytoextraction may not be feasible in the remediation of lead. Phytostabilization could be considered as a better alternative as it immobilizes lead in the environment through rhizosphere, hence reducing exposure though it does not remove lead from soil. It is to be noted, while aiming to be as comprehensive as possible, this review might not have included all studies with plants fully or partially demonstrating the features of a lead hyperaccumulator.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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