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Practices for Phytoremediation of Soil in Serbia

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ABSTRACT

Phytoremediation stands as a crucial tool for addressing pollution, yet its application in Europe remains inadequately explored. Taking Serbia as a test case, this literature review delves into the state of knowledge regarding phytoremediation, exploring the regional distribution of contaminated sites, the prevalence of analysed contaminants, and the diversity of plant species employed for phytoremediation. Analysis revealed 24 distinct locations, 11 sampling parts, scrutiny of 24 potential toxic elements (PTEs) and nutrients, and the involvement of 65 plant species. Predominantly, research sites were associated with industrial areas, particularly mining sites. The efficacy of various plants varied across multiple factors, with soil, roots, and leaves emerging as the most frequently sampled components in reviewed manuscripts. Notably, the scientific literature emphasized Cu, Zn, Cd, and Pb as the most frequently studied PTEs in the context of phytoremediation. This review underscores the need for increased attention to phytoremediation research in Serbia, advocating a more widespread and intensive exploration, both geographically and in research efforts. The compilation of plant species employed for phytoremediation offers valuable insights into the effectiveness of particular species in distinct phytoremediation practices.

Keywords: potential toxic elements (PTEs); soil pollution; plant uptake; soil reclamation; phytostabilisation; biomonitoring

INTRODUCTION

Phytoremediation is an environmentally friendly technology that uses plants to clean up various contaminated sites (Pilon-Smits 2005, Jiang et al. 2024). It is a sustainable, eco-friendly treatment method for contaminated soil, water, and air that entails procedures including removing, transferring, stabilising, or degrading pollutants from these ecosystems (Haynes 2009, Wei et al. 2021). Despite its promising aspects, phytoremediation also has certain limits (Drzewiecka et al. 2024). The effectiveness of phytoremediation techniques depends on various factors, such as plant species, field conditions, desired cleanup goals, and the nature of contaminants present. These techniques include phytostabilization/phytoimmobilization for lowering the mobility of contaminants and phytovolatization/phytoextraction for the removal of pollutants (Bortoloti and Baron 2022). Furthermore, the justification for implementing phytoremediation is also the opportunity for cost-effective remediation (Ghosh and Singh 2005).

Phytoremediation is one of the most effective solutions for solving environmental pollution, with a specific focus on the challenges posed by heavy metals. Within the domain of literature, particularly in the context of environmental pollution, the term "heavy metals" refers to a set of elements that are classified based on their density or molar mass (Zhang et al. 2019). This category encompasses not only metals but also metalloids and nonmetals, without a precise definition. The phrase in question is deemed ambiguous by the International Union of Pure and Applied Chemistry due to the lack of a recognized definition. Consequently, a comprehensive category of elements investigated in the environment has been referred to as "potentially toxic elements (PTEs)" (Pourret and Hursthouse 2019). PTEs primarily consist of trace elements that are essential for the growth and development of plants (e.g., Zn, Cu), but can become toxic at higher concentrations, as well as of other elements (e.g., As, Cd, Hg, Ni, and Pb), which have a harmful effect on the living world even in small quantities (Belanović Simić 2017). PTEs cannot be degraded by biological or chemical processes, and therefore they are accumulated in various environments such as soil, sediments, water, as well as in living organisms (Sun et al. 2013). Pollution by PTEs can occur as a result of both natural (rock weathering, volcanic eruptions) and human activities (industry, urbanisation, intensive agriculture, etc.) (Ali et al. 2013). PTEs derived from natural sources are less harmful to the environment in general, while metals derived from anthropogenic sources represent a hazard to the environment as well as to human health (Jaishankar et al. 2014, Muthusaravanan et al. 2018).

Mining represents one of the most significant drivers of soil and water pollution, and it is well-known for its negative effects on the ecosystem (Jakovljević et al. 2019). Even when mining operations in a particular location are over, waste material dumps continue to harm the environment for an extended period of time (Fernández-Caliani et al. 2009). The disposal of fly ash can pose a hazard since the leaching of PTEs may further have a negative impact on the ecosystem (Pandey and Singh 2010). To reduce environmental pollution, plant species that are resistant to the particular mixture of abiotic stress factors occurring in the contaminated environment, and which can develop self-sustaining vegetation cover, would be beneficial (Pietrzykowski et al. 2018). Growing in highly polluted environments, some plant species can be severely harmed, while others can endure with no noticeable alterations (Marić et al. 2013). PTEs can be taken up by plants via roots from the soil and then transported to the leaves, or by leaves straight from the air (Alagić et al. 2013).

PTEs contamination of soil presents a huge risk to the environment and humans (Shah and Daverey 2020). Various regions worldwide, such as the USA, China, Central-Eastern Europe, and others, grapple with finding solutions to PTE's contamination, although the nature of the problem varies across regions (Yao et al. 2012, Sharma and Pandey 2014). Serbia, too, faces similar challenges, necessitating new knowledge, solutions, and achievements. In relation to this, our research contributes to filling this gap through the following goals:

- Assess the state of knowledge regarding phytoremediation practices in Serbia by reviewing scientific literature;
- Assess the performance of plant species used for phytoremediation and the frequency of various contaminants (PTEs and nutrients).

MATERIALS AND METHODS

We reviewed scientific publications pertaining to the application of techniques for phytoremediation of soil related to the territory of Serbia. A literature review was performed using data from the Web of Science multidisciplinary research engine, which has been recognised as a trusted source of high-quality peer-reviewed papers. A keyword-based search on Web of Science was conducted between April and September 2023. To categorise and manage all the papers, this research built a database based on the following combination of keywords: "phytoremediation OR phytostabilization OR phytoextraction OR phytovolatilization AND "Serbia". These terms were used to search in all fields. Papers in English and Serbian language were considered, while publication date was not used as a selection criterion. For performing this review, we used the Rayyan (http://rayyan.qcri.org) online application for systematic reviews by Ouzzani et al. (2016). All identified papers' abstracts were reviewed. Intensive manual interpretation was performed in order to obtain a set of papers related to phytoremediation experience in Serbia. Articles were considered relevant if they were related to some phytoremediation practices within the territory of Serbia. In cases where the article was related to Serbia and other countries, only results related to Serbia were considered relevant and analyzed. A full text analysis was conducted for the selected number of publications. Additionally, the review was supplemented with a backward snowball search, which included a review of selected references cited in the reviewed articles.

RESULTS AND DISCUSSION

In total, 155 papers were obtained. Finally, 31 papers were selected as suitable for an overview. The analysis of the papers included 24 different locations in Serbia, while 65 different plant species were detected as the ones used for phytoremediation practice. Furthermore, we established that the analysed studies contained 11 different sampling parts (soil and specific plant parts). The identified studies were related to 24 detected PTEs in total.

Analysed Locations

Papers covered various locations in Serbia (Figure 1). The majority of them were related to the vicinity of mining sites, as these may be the most hazardous ones. Other sites were related to the landfill, some specific source of pollution, municipalities, or experimental study sites. Most of the reviewed studies were performed in the area or vicinity of Bor municipality (eastern Serbia). The reason for this could be found in the copper mining and smelting complex RTB Bor, whose surrounding area acts as a phytoremediation laboratory. Similar to this, other two locations—the vicinity of thermal power plant TENT and Rudnik mine—were also recognised as common locations for phytoremediation practices.

Analysed Species Used for Phytoremediation Practices

Various plant species (65) were applied in the analysed papers for phytoremediation practice. These species have been divided into the following five groups: 1) shrubs or small trees; 2) trees; 3) annual or biennial plants; 4) perennial plants; and 5) crops.

Shrubs or Small Trees

In this category, eight species were identified and analysed in the reviewed papers (Table 1). The detected species showed various results depending on multiple factors. For example, in terms of phytostabilization, three species were marked as potentially suitable. Among them, *Tamarix tetrandra* Pall. Ex M. Bieb. was recognised as the one with the highest potential in terms of phytostabilization of PTEs such as As, Cr, and Ni (Kostić et al. 2021). Nevertheless, this species showed that it is not suitable for phytostabilization

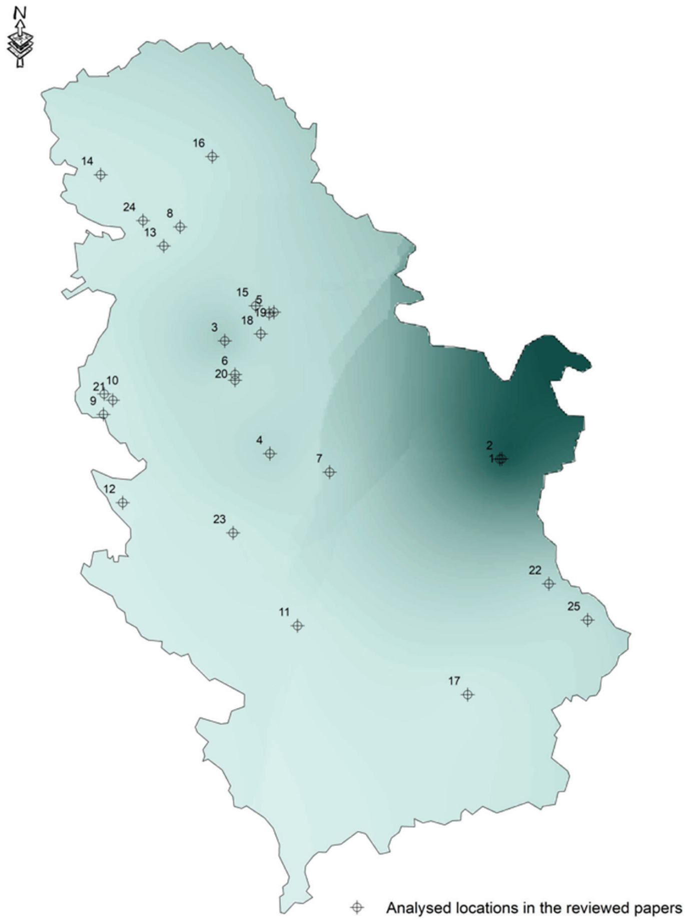

Figure 1. Analysed locations in the reviewed papers, where numbers represent locations given on the map. Areas with a darker colour gradient indicate a higher frequency of research. Locations: (1) - RTB Bor, (2) - Bor municipality, (3) - TENT, (4) - Rudnik mine tailings pond, (5) - Botanical garden “Jevremovac”, (6) - Thermoelectric power plant “Kolubara” landfill, (7) - Near highway at the entrance into the city of Kragujevac, (8) - The Experimental Estate of the ILFE, Novi Sad, (9) - Veliki Majdan deposit, (10) - Stolice deposit, (11) - Flotation tailings near Ibar river and Rudnica village, (12) - Entrance to the Derventa River Canyon on Mt. Tara, (13) - Fruška Gora, (14) - Odžaci, (15) - The unpolluted soil at the INEP, Zemun, (16) - The Great Bačka Canal in the vicinity of Vrbas, (17) - “Lece” mine, (18) – Orlovača, (19) - The urban area of Ada Huja, (20) - Coal mine waste overburden site (Tamnava), (21) - A flotation tailings pill (Krupanj), (22) – 20 km far from the uranium mine Gabrovnica-Kalna, (23) - The village of Kotraža, (24) – The village of Gložan, (25) - Stara Planina Mt.

on fly ash sites (Kostić et al. 2022). *Salix viminalis* L. clone ‘SV068’ showed the ability to phytostabilize Cr, Ni, Pb, and Cu, mostly in the root zone (Pilipović et al. 2019). *Rubus fruticosus* L. was also marked as a species with potential for phytostabilisation practice (Alagić et al. 2016, Alagić et al. 2017). In terms of phytoextraction, *T. tetrandra* (Kostić et al. 2021, 2022), *Salix viminalis* L. clone ‘SV068’ (Pilipović et al. 2019) and *Rubus fruticosus* L. (Alagić et al. 2017, Alagić et al. 2016) were recognised as suitable species. *Vaccinium uliginosum* L. showed the greatest tendency to mobilise Cd and Cu compared to *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea* L., while both of these species could be used on soils with elevated Cd levels (Belanović et al. 2013). The rest of the analyzed species from this group showed a tendancy towards other phytoremediation practices, respectively *Amorpha fruticosa* L. - sustainable phytomanagement (Kostić et al. 2021) and *Salix caprea* L. - bioaccumulator (Brković et al. 2021).

Tree Species

Seventeen tree species were detected among the reviewed papers shown in Table 2. Among them, *Aesculus hippocastanum* L., *Betula pendula* Roth, *Acer platanoides* L. (Gorelova et al. 2011), *Betula* sp. (Alagić et al. 2013, 2014) and *Tilia* sp. (Gorelova et al. 2011, Alagić et al. 2013, 2014) were detected as potentially suitable candidates for biomonitoring practices. *Fraxinus ornus* L. (Brković et al. 2021) and *Populus deltoides* Bartr. ex Marsh.‘Bora’

Table 1. Shrubs or small tree species analysed in the reviewed papers.

Species	Result	Reference
Tamarix tetrandra Pall. Ex M. Bieb.	Significant phytostabilization of As, Cr, and Ni, as well as the ability for the phytoextraction of Se and the accumulation of vital Mn, Zn, and Cu in settings where their bioavailability in fly ash is low. Not suitable for use in the phytostabilization of fly ash.	Kostić et al. 2021, 2022
Salix caprea L.	Efficient bioaccumulator of Fe, Cu, Cr, Mg and Pb.	Brković et al. 2021
Amorpha fruticosa L.	Could be applied for the sustainable phytomanagement of fly ash disposal sites.	Kostić et al. 2021
Salix viminalis L. clone 'SV068'.	Zn and Cd accumulation was mostly present within leaves, which indicated successful phytoextraction, while phytostabilization of Cr, Ni, Pb, and Cu was in the root zone.	Pilipović et al. 2019
Rubus fruticosus L.	Could be a promising candidate for different phytoremediation processes in the case of both organic and inorganic pollutants. Could be used for phytoextraction and phytoaccumulation in roots, as well as for phytostabilization and rhizodegradation processes.	Alagić et al. 2016, 2017
Vaccinium myrtillus L.	Able to perform well on soils with higher content of Cd, without a substantial danger of its accumulation.	Belanović et al. 2013
Vaccinium uliginosum	Has high contents of Cd and Zn. An increase in the Zn concentration in both soil and *V. uliginosum* plants improved the accumulation of Cd in aboveground plant parts. Poses a high affinity to mobilizable Cd and Cu.	Belanović et al. 2013
Vaccinium vitis-idaea	Able to perform well on soils with higher content of Cd, without a substantial danger of its accumulation.	Belanović et al. 2013

(Pilipović et al. 2019, 2020) both showed the ability for phytoextraction, while *Tilia* sp. and *Betula* sp. were not suitable for phytoextraction practices (Alagić et al. 2013, 2014). Nevertheless, these two species showed to be of interest as phytostabilization species (Alagić et al. 2013, 2014), while *Robinia pseudoacacia* L. and *Populus alba* L. were recognised as not suitable for phytostabilization on fly ash (Kostić et al. 2021). *Populus deltoides* Bartr. ex Marsh.'Bora', *Populus deltoides* 'PE 19/66' and *Populus* x *euramericana* (Dode) Guinier 'Pannonia' have shown similar reactions to PTEs, diesel, and herbicide treatments, where PTEs had a more significant effect on growth and physiology as the trees matured, while diesel and herbicide treatments were most pronounced during the first growing season, with diminishing effects over time (Trudić et al. 2013, Pilipović et al. 2020). Furthermore, in research by Trudić et al. (2013), two poplar clones, *Populus euramericana*-M1 and *Populus deltoides* B 229, were recognised as primary and secondary clones, respectively, in terms of potential application for phytoremediation in soil ecosystems that are polluted by PTEs. *Populus nigra* L. was efficient for the accumulation of Mn and Cd, while *Salix alba* L. was recognised as a useful bioaccumulator of Mn, Fe, Cr, Pb, Zn, and Ca (Brković et al. 2021). *Quercus petraea* (Matt.) Liebl. and *Quercus robur* L. both showed significantly high concentration of Mn and Fe within foliage, while concentrations of Zn and Cu were slightly higher in branch material (Stojnić et al. 2019).

Annual and Biennial Plant Species

Eight annual or biennial plant species have been identified and are presented in Table 3. *Tripleurospermum inodorum* (L.) Sch.Bip. (syn. *Matricaria inodora* L.), *Crepis setosa* Haller fill. (Glisic et al. 2021) and *Erigeron canadensis* L. (syn. *Conyza canadensis* L.) (Krgović et al. 2015, Vukojević et al. 2016) showed to be efficient for phytoextraction and phytostabilization purposes. *Vicia sativa* L., *Ranunculus arvensis* L., *Amaranthus retroflexus* L., and *Galium aparine* L. all showed a high accumulation of Cu, while the accumulation of Pb was slight (Marić et al. 2013). *Euphorbia helioscopia* L. proved to be valuable for biomonitoring purposes (Petrović et al. 2021).

Perennial Plant Species

The majority of the analysed plants were perennial, comprising twenty-eight species, as summarised in Table 4. *Achillea millefolium* L. and *Saponaria officinalis* L. demonstrated potential suitability for phytoextraction practices (Nujkić et al. 2020, Glisić et al. 2021), while *Tussilago farfara* L. was recognised as not suitable for phytoextraction management (Jakovljević et al. 2020). *A. millefolium* (Nujkić et al. 2020, Glisić et al. 2021), *Dactylis glomerata* L. (Marić et al. 2013, Gajić et al. 2020), *Vitis vinifera* L. (Alagić et al. 2018), *Epilobium dodonaei* Vill. (Randjelović et al. 2016), and *Festuca rubra* L. (Gajić et al. 2016) manifested potential abilities for phytostabilization, while *Calamagrostis epigejos* (L.) had only certain potential for phytostabilization, but it was not recommended to be used as a single remediation choice (Randjelović et al. 2018). *Urtica dioica* L. (Petrović et al. 2021), *V. vinifera* (Alagić et al. 2018) and *Phragmites australis* (Cav.) Trin. ex Steud (Nikolić et al. 2014, Prica et al. 2019) were recognised as useful in biomonitoring practices. *Odontarrhena chalcidica* (Janka) Španiel, Al-Shehbaz, D.A.German & Marhold (syn. *Alyssum markgrafii* O.E. Schulz.) and *Odontarrhena muralis* (Waldst. & Kit.) Endl. (syn. *Alyssum murale* Waldst. & Kit.) both showed abilities to accumulate several elements and especially to act as hyperaccumulators for Ni, while *Alyssum montanum* L. showed higher concentrations of Mn in tissues than the two previously mentioned species (Branković et al. 2013). Certain species showed the tendency to accumulate Cu, such as *D. glomerata* (Marić et al. 2013, Gajić et al. 2020), *P. australis* (Nikolić et al. 2014, Prica et al. 2019), *Epilobium dodonaei* Vill. (Randjelović et al. 2016), *F. rubra* (Gajić et al. 2016), *Eryngium serbicum* Pančić, *Sanguisorba minor* Scop. (Branković et al. 2015) *Euphorbia cyparissias* L., *Cynodon dactylon* L., *Anthoxanthum odoratum* L., *Lollium perenne* L., *Agrostis gigantea* L., *Trifolium pratense* L., *Medicago falcata* L., *Lotus corniculatus* L., *Helleborus odorus* L., *Equisetum*

Table 2. Tree species analyzed in the reviewed papers.

Species	Result	Reference
Robinia pseudoacacia L.	Cr root-shoot transfer is low. It is not recommended for utilisation in the phytostabilization of fly ash.	Kostić et al. 2021
Populus alba L.	Cr root-shoot transfer is low. It is not recommended for utilisation in the phytostabilization of fly ash.	Kostić et al. 2021
Populus nigra L.	Efficiently accumulates Mn and Cd.	Brković et al. 2021
Fraxinus ornus L.	Ability of Ca phytoextraction	Brković et al. 2021
Salix alba L.	Successfully bioaccumulates Mn, Fe, Cr, Pb, Zn and Ca	Brković et al. 2021
Populus deltoides Bartr. ex Marsh.'Bora'	PTEs had a greater impact on physiology and growth as the trees developed, whereas diesel and herbicide treatments were significant in the first season. Clone 'Bora' exhibited 13.8 times greater biomass than 'Pannonia'. Zn and Cd were predominantly found in leaves, which indicated successful phytoextraction. The roots phytostabilize Cr, Ni, Pb, and Cu.	Pilipović et al. 2019, 2020
Populus deltoides 'PE 19/66'	PTEs had a greater impact on physiology and growth as the trees developed, whereas diesel and herbicide treatments were significant in the first season. The biomass of clone 'PE' was 19.6 times that of clone 'Pannonia'.	Trudić et al. 2013, Pilipović et al. 2020
Populus x *euramericana* (Dode) Guinier 'Pannonia'	PTEs had a greater impact on physiology and growth as the trees developed, whereas diesel and herbicide treatments were significant in the first season.	Pilipović et al. 2020
Quercus petraea (Matt.) Liebl.	Mn and Fe concentrations were substantially greater in the foliage, while Zn and Cu concentrations were somewhat higher in the branches.	Stojnić et al. 2019
Quercus robur L.	Mn and Fe concentrations were substantially greater in the foliage, while Zn and Cu concentrations were somewhat higher in the branches.	Stojnić et al. 2019
Tilia sp.	Not suitable for Ni phytoextraction, however, might be useful for phytostabilization in the case of As and Cd. Suitable candidate for biomonitoring purposes. It can be used for biomonitoring the environment for PTEs, such as Fe.	Gorelova et al. 2011, Alagić et al. 2013, 2014
Betula sp.	Not suitable for Ni phytoextraction, however, might be useful for phytostabilization in the case of As and Cd. Suitable candidate for biomonitoring purposes. May provide more useful information than *Tilia* sp. regarding As and Cd within the environment.	Alagić et al. 2013, 2014
Populus euramericana-M1	The M1 clone exhibited a more acceptable antioxidative response in shoots compared to the B229 and PE 19/66 clones. Marked as the primary clone in the application of phytoremediation of PTEs impaired soils.	Trudić et al. 2013
Populus deltoides B 229	Showed a more acceptable antioxidative answer through leaves and roots. Marked as a secondary clone in the application of phytoremediation of PTEs impaired soils.	Trudić et al. 2013
Aesculus hippocastanum L.	Can be used for biomonitoring of environment for PTEs: Ni and Pb.	Gorelova et al. 2011
Betula pendula Roth	Can be used for biomonitoring of environment for PTEs: Mn, Fe, Ni, Zn, Cd and Pb.	Gorelova et al. 2011
Acer platanoides L.	Can be used for biomonitoring of environment for PTEs: Mn and Fe.	Gorelova et al. 2011

arvense L., and *Taraxacum* sect. *Taraxacum* F.H.Wigg. (Marić et al. 2013). Furthermore, *Miscanthus* × *longiberbis* (Hack.) Nakai (syn. *Miscanthus × giganteus)* was able to manage extremely harsh conditions in the flotation tailings while retaining the accumulated metals (Zn, Pb, and Cu) within the root zone, being recognised as an excluder of Cu, Zn, and especially Pb (Andrejić et al. 2019).

Crops

Three crop species were determined, each with four different inbred lines or sorts (Table 5). On average, soybean demonstrated the highest efficiency in uranium accumulation (root and shoot) when cultivated in both regular soil and tailing soil conditions (Stojanović et al. 2016). However, due to some results that varied among different cultivars, uranium uptake was not only based on substrate types but also on specific cultivars (Stojanović et al. 2016).

Native, Non-native, Hybrids, Clones, and Crops

Previously described species were further divided into native and non-native species, while hybrid, clone, and crop species were categorised separately (Figure 2). The native species had the highest proportion, while non-native species, hybrids, clones, and crops species were utilised less frequently. Even though sites for phytoremediation practices may be very challenging for plant species and likely more suitable for invasive plant species, the high share of native plant species used is an encouraging practice. Invasive plants are recognised as a serious threat to the environment, even to the biosphere itself, but despite that, they are valued in

Table 3. Annual and biennial plant species analysed in the reviewed papers.

Species	Result	Reference
Tripleurospermum inodorum (L.) Sch.Bip. (syn. *Matricaria inodora* L.)	May be utilised for phytoextraction of Ca, Mg, Fe, Mn, Cu, Zn, and Cr (leaves) and Cr (stem). Suitable for phytostabilization and phytoremediation of Zn.	Glisić et al. 2021
Euphorbia helioscopia L.	Useful in biomonitoring. Showed to be more efficient than *Urtica dioica* L. in the extraction, translocation, and bioaccumulation of metals, particularly Cu.	Petrović et al. 2021
Crepis setosa Haller fill.	May be utilised for phytoextraction of Ca, Mg, and Cu (leaves). Suitable for phytostabilization and phytoremediation of Zn.	Glisić et al. 2021
Erigeron canadensis L. (syn. *Conyza canadensis* L.)	The plant retained Al, Fe, and Cr in the root while translocating Zn, Cd, Cu, and As from the root to the shoot. Suitable for phytostabilization. The shoot may contain higher concentrations of Zn, Cu, and Cd. Can be used to remove Cd and Zn from coal ash landfills using phytoextraction.	Krgović et al. 2015, Vukojević et al. 2016
Vicia sativa L.	It could be used for phytoremediation in polluted areas. Cu accumulation was quite high, considerably higher than in polluted plants, although Pb accumulation was minimal.	Marić et al. 2013
Ranunculus arvensis L.		
Amaranthus retroflexus L.		
Galium aparine L.		

Table 4. Perennial plant species analysed in the reviewed papers.

Species	Result	Reference
Urtica dioica L.	Useful in biomonitoring	Petrović et al. 2021
Achillea millefolium L.	Metallophyte. This specie can be applied to extract Ca, Mg, Fe, Mn, Cu, Zn, and Cr from soil and translocate them to the leaves. Suitable for phytostabilization of Zn-rich soils. Phytoextraction of Pb, and As from polluted soil might be considered.	Nujkic et al. 2020, Glisić et al. 2021
Saponaria officinalis L.	Metallophyte, in polluted environments, this plant is suitable for phytoextraction of Pb and As.	Nujkić et al. 2020
Dactylis glomerata L.	It has a high ecophysiological adaptation ability, allowing it to thrive and survive on As-contaminated soil. On fly ash deposits, it is an excluder plant as it keeps As mostly in its roots rather than its leaves, indicating that this grass has a strong phytostabilization capacity for As. Cu accumulation was quite high, considerably higher than in polluted plants, although Pb accumulation was minimal.	Marić et al. 2013, Gajić et al. 2020
*Tussilago farfar*a	Although it is not a good choice for phytoextraction of Ca, Mg, Fe, S, Al, Pb, Zn, Cu, Cd, Mn, As, Sb, Ag, Ti, and Sr, as a pioneer species with high ecological adaptability, it plays an important role in the early stages of revegetation in severely polluted areas and in preventing the dispersal of pollutants to nearby environments.	Jakovljević et al. 2020
Miscanthus × longiberbis (Hack.) Nakai (syn. *Miscanthus × giganteus*)	Plants kept the majority of deposited PTEs (Zn, Pb, and Cu) inside the roots and revealed limited translocation to shoots, preventing these contaminants from reaching the food chain. Recognised as an excluder of Cu, Zn, and particularly Pb.	Andrejić et al. 2019
Phragmites australis (Cav.) Trin. ex Steud	The highest concentrations of PTEs found in plant roots suggest that common reed can be employed effectively in rhizofiltration of wastewaters as well as in phytostabilization and regeneration of heavy metal-contaminated sites. The substantial N, P, and K concentrations in certain parts of common reed imply that it is an effective phytoaccumulator of these essential nutrients.	Nikolić et al. 2014, Prica et al. 2019
Vitis vinifera	Assimilated Fe and Mn can be particularly efficient in various biomonitoring processes, as well as for phytostabilization.	Alagić et al. 2018
Calamagrostis epigejos (L.)	Even though it indicates a certain potential for metal phytostabilization, it does not offer an ideal choice as a single remediation option. This is due to the fact that the share of the available fraction's part is low in comparison to the total amount of heavy metals at the analysed sites.	Randjelović et al. 2018
Epilobium dodonaei Vill.	Has a greater concentration of As and Cu in the shoots when grown in mine waste areas. This species, on the other hand, maintains Cu, Pb, and Zn mostly in roots rather than shoots and has the ability to phytostabilize metalliferous mine sites. Can be an acceptable species for restoration across a broader regional range of diverse metallogenic provinces.	Randjelović et al. 2016

Table 4. (continue) - Perennial plant species analysed in the reviewed papers.

Species	Result	Reference
Festuca rubra L.	Has the capacity to phytostabilize fly ash deposits due to a densely tufted root structure. Has the potential to retain more As, Cu, Mn, and Zn in the root system than in the foliage.	Gajić et al. 2016
Odontarrhena muralis (Waldst. & Kit.) Endl. (syn. Alyssum murale Waldst. & Kit.)	Accumulated the most of Ni.	Branković et al. 2015
Eryngium serbicum Pančić	Ability for accumulation of Cu.	Branković et al. 2015
Euphorbia cyparissias L.	Since it is capable of accumulating Zn and Cu, it could be used in phytoremediation of polluted areas. Able to accumulate high concentrations of Cu, considerably greater than in polluted plants, although Pb accumulation is relatively low.	Maric et al. 2013, Branković et al. 2015
Sanguisorba minor Scop.	A high tolerance to several PTEs. Has the ability for the accumulation of Cu. High content of Mg.	Branković et al. 2015
Cynodon dactylon L. *Anthoxanthum odoratum* L. *Lollium perenne* L. *Agrostis giganthea* L. *Trifolium pratense* L. *Medicago falcata* L. *Lotus corniculatus* L. *Helleborus odorus* L. *Equisetum arvense* L. *Taraxacum sect. Taraxacum F.H.Wigg.*	It could be used for phytoremediation in polluted areas. Cu accumulation was quite high, considerably higher than in contaminated vegetation, although Pb deposition was minimal.	Marić et al. 2013
Odontarrhena chalcidica (Janka) Španiel, Al-Shehbaz, D.A.German & Marhold (syn. Alyssum markgrafii O.E. Schulz.)	Showed better phytoaccumulation of Mg and Pb than *A. murale*. Showed better phytoaccumulation of Ca, Zn, Ni, and Pb than species *A. montanum*. Recognised as a nickel hyperaccumulator.	Branković et al. 2013
Alyssum murale Waldst. & Kit.	Showed better phytoaccumulation of Ca, Fe, Mn, Cu, Zn, Ni, Cd, Co, and Cr than *A. markgrafii*. Showed better phytoaccumulation of Ca, Zn, Ni, and Pb than species *A. montanum*. Recognised as a nickel hyperaccumulator.	
Alyssum montanum L.	It showed higher concentration of Mn in its tissues than *A. murale* and *A. markgrafii*, as well as higher concentration of Cu than *A. markgrafii*.	

Table 5. Crops analyzed in the reviewed papers.

Species	Result	Reference
Corn-inbred lines: 316207, 326037, MO17HZ and B73H7	Uranium concentration in shoot, grown on soil – low. Uranium concentration in shoot, grown in tailing soils – medium. Uranium concentration in root, grown on soil – low. Uranium concentration in root, grown in tailing soils – medium.	Stojanović et al. 2016
Sunflower – 4 sorts coded from I to IV	Uranium concentration in shoot, grown on soil – medium. Uranium concentration in shoot, grown in tailing soils – low. Uranium concentration in root, grown on soil – medium. Uranium concentration in root, grown in tailing soils – low.	
Soybean - 4 sorts: Kolubara, Vera, Ravanica and Balkan	Uranium concentration in shoot, grown on soil – high. Uranium concentration in shoot, grown in tailing soils – high. Uranium concentration in root, grown on soil – high. Uranium concentration in root, grown in tailing soils – high.	

phytoremediation practice for their high tolerance, wide distribution, and rapid growth (Khan et al. 2023). It cannot be disregarded that invasive plants are opportunists, and once established in a naturalised environment, it is almost impossible to eradicate them completely (Prabakaran et al. 2019). The spread of exotic and invasive species poses a serious threat, especially for vulnerable habitats such as wetlands. It may lead to the disruption of natural balance, displacement or extinction of the characteristic species, or even native biota loss (Yang et al. 2005, Leguizamo et al. 2017). Therefore, it is necessary to weigh the risk of the use of exotic and invasive species and their ability to offer substantial ecologically viable services for the sake of achieving holistic management of the entire environmental setting (Prabakaran et al. 2019).

Most Used Species

Out of the 65 previously mentioned plant species, certain ones have been featured in multiple research papers. *Tilia sp.* (Gorelova et al. 2011, Alagić et al. 2013, 2014,) and *Betula sp.* (Gorelova et al. 2011, Alagić et al. 2013, 2014,) have been identified in three different studies and are, as such, the most commonly used species according to reviewed scientific literature. In addition, the following species have been identified in two different studies: *Tamarix tetrandra* Pall. Ex M. Bieb. (Kostić et al. 2021, 2022); *Achillea millefolium* L. (Nujkić et al. 2020, Glisić et al. 2021,); *Rubus fruticosus* L. (Alagić et al. 2016, 2017); *Erigeron canadensis* L. (*Conyza canadensis* L.) (Krgović et al. 2015, Vukojević et al. 2016); *Euphorbia cyparissias* L. (Branković et al. 2015, Marić et al. 2013); *Dactylis glomerata* L. (Marić et al. 2013, Gajić et al. 2020).

Analysed Samples

The analysed studies were conducted on various samples such as soil, roots, leaves, shoots, stem/stalk, fly ash, rhizomes, whole plants, litterfall, branches, and inflorescences. The majority of studies included samples of soil, roots, and leaves, while the minority related to litterfall, branches, and inflorescences (Figure 3).

The observed results may indicate that most phytoremediation techniques incorporate considerations of the soil's condition. Moreover, given that the examination of roots has been widely acknowledged, it may be concluded that the practice of phytostabilization is the most employed. Other frequently examined parts, including leaves, shoots, and stems, may provide indications of phytoextraction techniques. Furthermore, given the existence of multiple studies focusing on fly ash areas, it can be assumed that there is a demand for the implementation of phytoremediation techniques in such sites. Our literature review did not identify any existing research that has investigated the implementation of phytovolatilization practices.

Analysed PTEs and Nutrients

Multiple studies have been conducted to investigate the occurrence of different elements in soil ecosystems. The PTEs identified in these studies include Cu, Zn, Cd, Pb, Ni, Mn, Fe, As, Cr, Ca, Mg, Co, B, Al, Ag, Se, S, Ti, Ba, Sb, and U. Additionally, nutrients N, P, and K were identified. Most of the publications evaluated in this study focused on the investigation of Cu, Zn, Cd, Pb, Ni, Mn, Fe, As, and Cr, while other PTEs were less included (Figure 4).

The obtained findings may provide insight into the state of pollution sources and, subsequently, the most frequently encountered pollutants. Most of the analysed papers are related to the mining sites (especially RTB Bor), which reveals the predominant site distribution for phytoremediation practice so far. This further implies that specific site characteristics may also have a significant influence on the appearance of contaminants. However, it is important to consider that the obtained results could potentially be influenced to some degree by limited funding resources. For instance, sampling and analysis of some elements might be complex, expensive, and unfamiliar, thus hindering researchers from conducting such analyses.

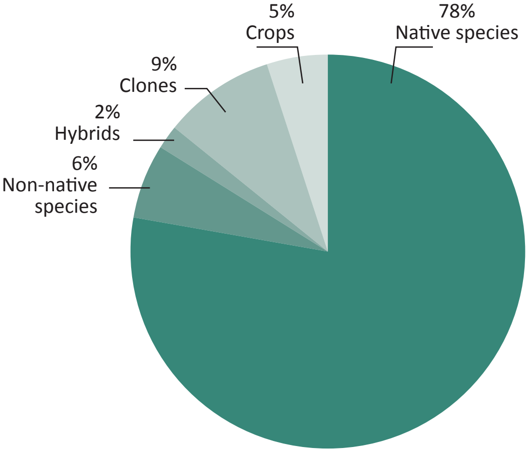

Figure 2. Native, non-native, hybrids, clones, and crops species used for phytoremediation practices in Serbia according to the reviewed literature.

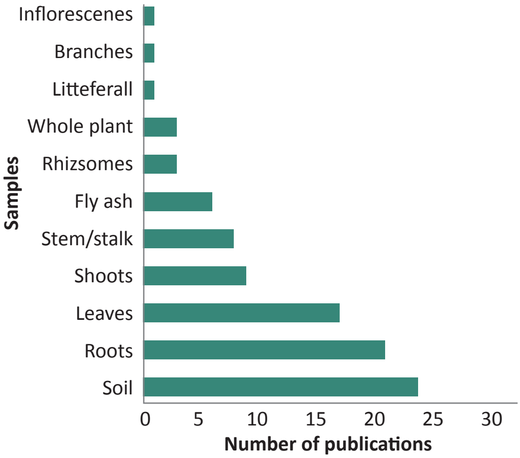

Figure 3. Different types of samples per publication number.

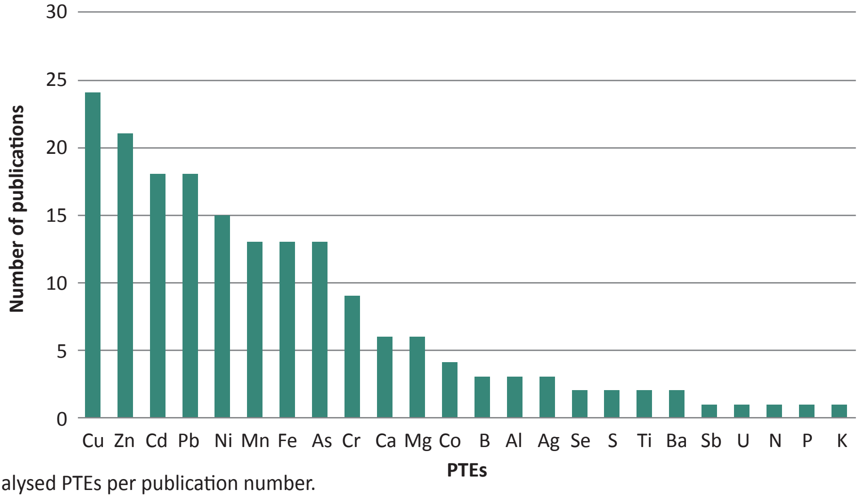

Figure 4. Analysed PTEs per publication number.

CONCLUSIONS

The examined body of scientific literature highlights the need for increased attention to phytoremediation research in Serbia, both in terms of its geographical distribution and research intensity. The summarised overview of plant species used for phytoremediation offers valuable insights into the potential efficiency of specific phytoremediation practices. However, it is crucial to acknowledge that the performance of various species may vary based on different factors. Additionally, combining multiple plant species may yield superior results compared to the application of a single species in phytoremediation practices. Whenever possible and feasible, native species should be prioritised, considering other relevant factors. Beyond the 65 species analysed, we recommend further research to explore the capabilities of additional native plants in the context of phytoremediation.

Author Contributions

FV, SBS, and SL developed the original idea and conceptualised the manuscript. FV conducted a review of the scientific literature and drafted the manuscript. SBS, DČ, MC, PM, NJ, AM, TG, and SL reviewed the drafted manuscript, performed editing, and critically revised the work. All authors have read and agreed to the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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