



PHYTOSTABILISATION IN MINE WASTE DUMPS: THE ROLE OF SELECTED TREE SPECIES IN THE LIGNITE MINES OF WESTERN MACEDONIA, GREECE

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Abstract: *This study investigates the potential of selected plant species for environmental restoration and phytostabilisation in lignite mine waste dumps in Western Macedonia, Greece. Field sampling was conducted in three representative sites, where both soil and plant tissues were collected and analysed using X-ray Fluorescence (XRF). A total of six species (*Pinus* spp., *Acacia* spp., *Populus* spp., *Cupressus* spp., *Cuprocyparis leylandii*, and *Tamarix* spp.) were evaluated for their ability to grow in low-fertility substrates and their capacity to accumulate potentially toxic elements (PTEs). The findings indicate that soil chemistry is primarily influenced by geogenic factors, with elevated concentrations of Ca, Si, Mg, and K, consistent with the carbonate-rich geology of the Ptolemaida basin. Concentrations of PTE (Ni, Cr, Zn, Pb) remain below established toxicity thresholds, and Hg levels are negligible (<0.03 mg/kg). Plant tissue analysis revealed selective nutrient uptake and limited translocation of PTEs to aerial parts. Although the studied species do not exhibit hyperaccumulator characteristics necessary for phytomining, they exhibit strong phytostabilisation capacity, supporting erosion control and ecological restoration without increasing environmental risk.*

Keywords: *Land reclamation; reforestation; phytostabilisation; potentially toxic elements (PTE); mine waste; soil-plant interaction.*

1. Introduction

Mining activities constitute a major driver of global economic development; however, they are frequently associated with significant environmental impacts, including land occupation for long periods, soil degradation, vegetation loss, and the formation of mine waste dumps [1]. The final surfaces of these dumps generally exhibit low organic matter content, limited nutrient availability, and unfavourable physicochemical properties unless covered with topsoil that was excavated from the upper horizon of the first mine bench. These characteristics hinder natural ecosystem recovery and plant establishment.

In many cases, mine waste may also contain elevated concentrations of potentially toxic elements (PTEs), which pose significant risks to environmental quality and human health. In addition, even when contamination

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levels are moderate, insufficient soil structure and fertility present a major limitation for successful revegetation.

Phytoremediation represents a sustainable and cost-effective strategy for the restoration of degraded lands. This approach encompasses a range of plant-based processes, including phytoextraction, phytostabilisation, rhizofiltration, and phytodegradation [2, 3, 4]. The selection of appropriate mechanism depends on site-specific conditions and remediation objectives.

Among these approaches, phytostabilisation is particularly suitable for mine waste environments. It focuses on reducing the mobility and bioavailability of contaminants through mechanisms such as root uptake, adsorption, and precipitation within the rhizosphere [5]. In addition, vegetation establishment contributes to erosion control and limits the dispersion of particulate matter.

In contrast, phytomining relies on hyperaccumulator plant species capable of extracting metals in economically viable quantities [6]. These species exhibit high translocation factors and accumulate metals within their above-ground biomass [7]. However, these conditions are rarely met in lignite mine environments, where metal concentrations are often moderate, and the primary objective is ecological stabilisation rather than resource recovery.

The effectiveness of phytoremediation systems depends significantly on soil properties, including pH, salinity, texture, and nutrient availability, in addition to the selection and adaptability of plant species [8]. Tree species such as *Pinus*, *Acacia*, *Populus*, and *Tamarix* are commonly used in mine rehabilitation due to their tolerance to harsh environmental conditions and their capacity to establish long-term vegetation cover.

Unlike hyperaccumulators, these species typically exhibit selective uptake mechanisms, favouring essential nutrients while limiting the translocation of PTEs to aerial tissues. This behaviour makes them particularly suitable for phytostabilisation applications.

This study aims to: (i) evaluate the growth and adaptability of selected tree species in lignite mine waste dumps, (ii) analyse soil and plant chemical composition, (iii) assess the behaviour of PTEs, and (iv) determine the suitability of these species for phytostabilisation applications.

To our knowledge, this study is the first to evaluate the role of selected tree species in lignite mines in Greece.

2. Study area

The study was conducted in the lignite mines of the Ptolemaida basin, Western Macedonia (Figure 1), one of the most important lignite-producing regions in Greece. The basin is part of the broader Bitola–Florina–Ptolemaida–Kozani tectonic trench of Miocene age and belongs to the Pelagonian geotectonic zone. The surrounding geological formations mainly consist of crystalline schists of the Pelagonian massif and their Mesozoic cover, while the Neogene sediments of the basin lie unconformably on this basement. These sediments include lacustrine marls, clays, sands, conglomerates, and lignite layers, reflecting a complex depositional environment [9].

The mineralogical composition of lignite and associated materials in the region includes quartz, feldspars, clay minerals, carbonates, and sulphates, along with trace amounts of sulphides and other minerals [10]. This geological heterogeneity plays a crucial role in determining the geochemical characteristics of mine wastes. Regarding the distribution of trace elements in lignite deposits, it is controlled by multiple factors, including the nature of the surrounding rocks, depositional environment, climatic conditions, hydrology, and post-depositional leaching processes [11]. As a result, both the overburden and lignite-bearing strata exhibit significant spatial variability in PTE concentrations.

In the study area, extensive surface mining activities occupy approximately 17,000 ha, including large dumping areas composed of waste rocks, excavated from overburden and lignite-bearing strata, and fly ash derived from lignite combustion in thermal power plants. Excavation and transport processes result in waste dumps containing a mixture of materials from various geological horizons, typically exhibiting poor structure, heterogeneous particle size distribution, low fertility, and limited organic matter content [12, 13]. These substrates are highly heterogeneous in both texture and geochemistry. Such heterogeneity is evident in reclaimed soils, which often show variable concentrations of trace elements but generally low solubility due to alkaline conditions and mineral binding [14]. Despite the presence of PTEs, their mobility is often restricted, as they are largely bound within mineral lattices or associated with Fe-/Mn oxyhydroxides, reducing their bioavailability to plants.

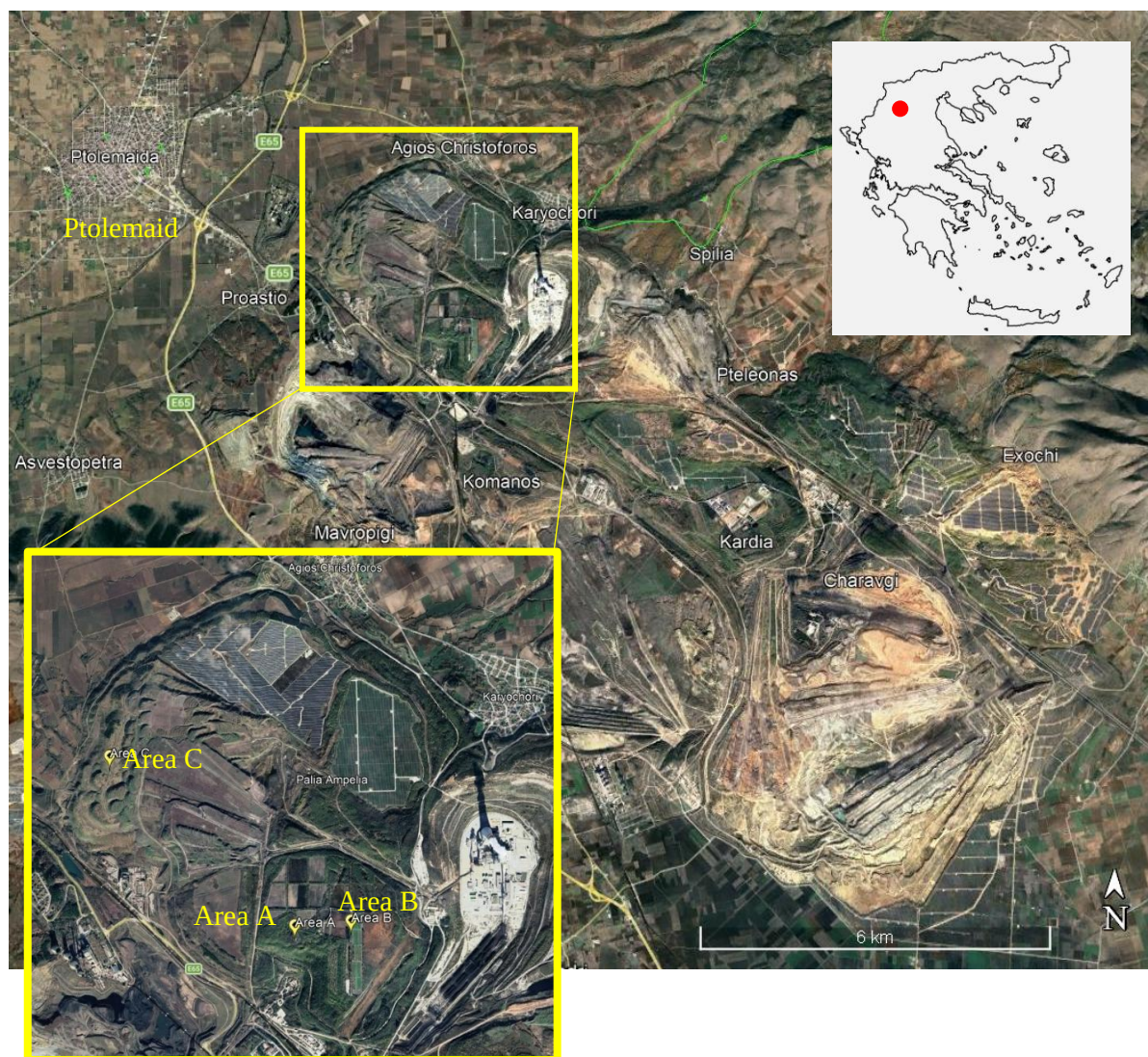


Fig. 1. Map of the study area (Google Earth, image date: 15 November 2025)

The regional climate is continental, with pronounced seasonal variability that influences soil development, vegetation establishment, and biogeochemical processes.

For this study, a total of three representative sampling sites were selected:

- Area A (Kiosk).
- Area B (Orchard).
- Area C (Western Slopes).

The study sites represent different stages of ecological restoration and land reclamation. The relatively flat Areas A and B were recontoured and reforested during the 1980s and 1990s, whereas the sloping Area C has undergone more recent restoration, approximately ten years ago. This gradient in reclamation age and geomorphology enables the evaluation of soil development and vegetation recovery under different restoration conditions.

3. Materials and methods

Field sampling was conducted in three representative mine waste dump areas (Kiosk, Orchard, and Western Slopes) using a targeted approach designed to capture soil–plant interactions under different vegetation conditions. Sampling locations were selected based on the presence of established tree species and site accessibility, ensuring representative coverage of the study area.

At each sampling point, soil samples were collected from the root zone near the selected trees, while corresponding plant samples were obtained from the same locations. This paired sampling strategy enabled direct comparison between soil and plant chemical composition and facilitated the assessment of element transfer mechanisms.

Soil samples were collected manually using hand tools and stored in sealed polyethylene bags to prevent contamination and moisture loss. Plant samples were collected using pruning tools and, where applicable, separated into different tissues (e.g., branches, leaves, and bark) to evaluate element distribution within the biomass.

All samples were subjected to standardized laboratory preparation procedures. Soil samples were air-dried and sieved to <1 mm to ensure homogeneity, while plant samples were oven-dried to constant weight. Subsequently, all samples were ground and homogenized prior to analysis. Moisture content was determined to allow accurate calculation of elemental concentrations on a dry weight basis.

Elemental analysis was performed using X-ray Fluorescence (XRF) technique, which enables rapid and simultaneous determination of major and trace elements in environmental samples. The analysis focused on major elements (Ca, Si, Mg, K) to characterise the geochemical background of the study area, as well as PTEs (Ni, Cr, Zn, Pb, Hg). Calibration procedures and internal quality control checks were applied to ensure analytical accuracy and reproducibility.

Data interpretation involved comparing measured concentrations with established environmental threshold values and evaluating soil–plant relationships. Specifically, the screening values used in this study were derived from Canadian soil quality guidelines for agricultural areas, as well as the intervention and trigger values for residential areas, defined by Dutch and German regulations, respectively [15, 16]. Emphasis was placed on identifying patterns of element uptake and translocation. The behaviour of the studied species was assessed by their ability to accumulate or exclude PTEs, allowing their classification as potential phytostabilisers or accumulators.

4. Results

4.1 Soil Composition

Soil analysis revealed high concentrations of major elements (Table 1), particularly Ca, reaching 35.4% in areas associated with *Tamarix spp.* Silicon, Mg, and K were also present at elevated levels. These results indicate a strong influence of the geological background rather than anthropogenic contamination.

Table 1. Concentrations of major elements in soil samples (mg/kg)

Elements	Area A		Area B		Area C	
	Populus spp.	Pinus spp.	Populus spp.	Cupressus spp.	Cuprocyparis leylandii	Tamarix spp.
Ca	169.659	169.560	306.028	335.687	310.421	354.375
Mg	12.593	15.664	10.678	8.800	8.640	3.780
Si	104.212	136.993	43.395	14.853	56.663	29.060
Al	38.824	55.530	19.493	6.172	26.166	11.742
K	8.048	11.560	3.880	1.339	3.592	1.595
P	447	546	571	349	506	293
S	890	1.301	1.658	1.381	2.304	1.642
Na	1.767	1.927	571			
Cl	130	142	140	151	117	
Fe	23.720	32.947	13.029	5.790	13.464	5.607
Ti	2.116	2.950	990	348	1.403	486

The concentrations of PTEs in the examined soil samples were generally below intervention thresholds (Table 2), suggesting limited environmental risk. Lead and Cd were not detected in any of the six samples analysed. The maximum Hg concentration recorded was 0.025 mg/kg, while Co (0.9 mg/kg) was detected in only one sample from Area B.

Table 2. Screening values for PTE concentrations (mg/kg) [17]

Soil quality guidelines or standards	Zn	Cu	Cd	Co	Cr
Soil quality guidelines for agricultural areas (Canada) [15]	200	63	1.4	40	64
Intervention values (Netherlands) [16]	720	190	12	240	380
Trigger values for residential areas (Germany) [16]			20		400

Figure 2 shows Zn and Cu concentrations in all study areas remained below action limits. However, Cr and Ni values were close to or slightly above threshold levels in Area A. This area has elevated concentrations of Si, Al, Fe, and Mn, with relatively lower Ca levels. This pattern likely reflects the dumping of waste rocks different from the marls and other calcareous rocks dominating the lignite deposit. The presence of such materials may explain the increased occurrence of PTEs, a finding that is also consistent with previous studies [18].

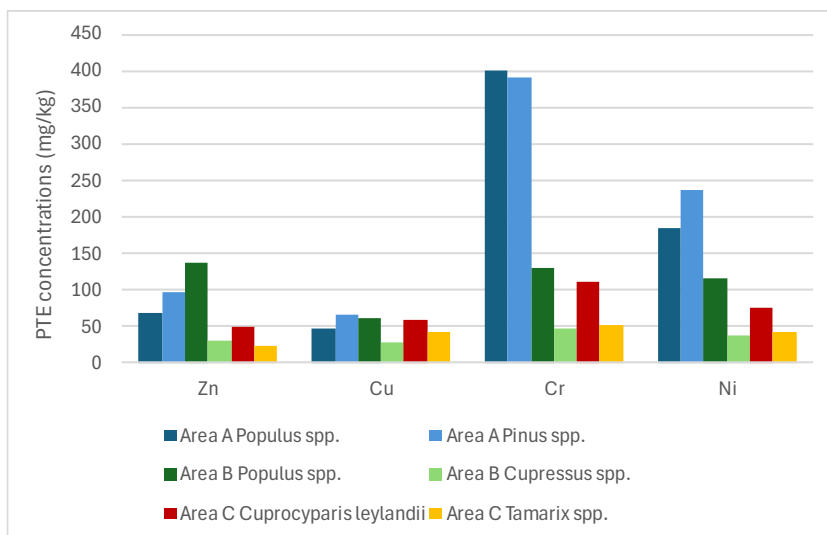


Fig. 2. Comparison of selected PTE concentrations in soil samples collected from the three reforested study areas

4.2 Plant Tissue Analysis

Plant tissues exhibit elevated concentrations of essential nutrients, particularly Ca and K (Table 3), with generally low accumulation of PTEs. This pattern suggests a tendency toward selective nutrient uptake while limiting internal transfer of PTEs. Specifically, *Acacia* spp. had notably high Ca concentration (approximately 2.48%) combined with minimal uptake of PTEs, indicating an effective exclusion or stabilization mechanism. *Tamarix* spp., showed elevated S and Cl concentrations, reflecting physiological adaptations to saline or stressed environments. Finally, *Populus* spp. demonstrated low Cr translocation, further supporting the observation that movement of certain PTEs to aerial plant tissues remains limited (Figure 3).

Table 3. Concentrations of major elements in plant tissue samples (mg/kg)

Elements	Area A		Area B			Area C	
	Populus spp.	Pinus spp.	Acacia spp.	Populus spp.	Cupressus spp.	Cuprocyparis leylandii	Tamarix spp.
Ca	38.392	10.081	24.780	48.336	35.293	33.980	13.154
Mg	2.796	1.001	1.731	1.470	1.152	1.173	4.519
Si	1.331	2.113	2.946	753	2.528	6.351	1.268
Al	456	1.047	1.353	346	1.113	2.342	613
K	5.203	3.326	14.851	1.290	5.079	4.465	7.402
P	1.103	507	1.259	706	644	896	1.107
S	1.089	650	1.720	1.512	1.184	1.216	14.458
Na							1.339
Cl	149	175	323	102	749	439	5.129
Fe	299	549	785	224	414	1.285	268
Ti		44	63		29	115	24

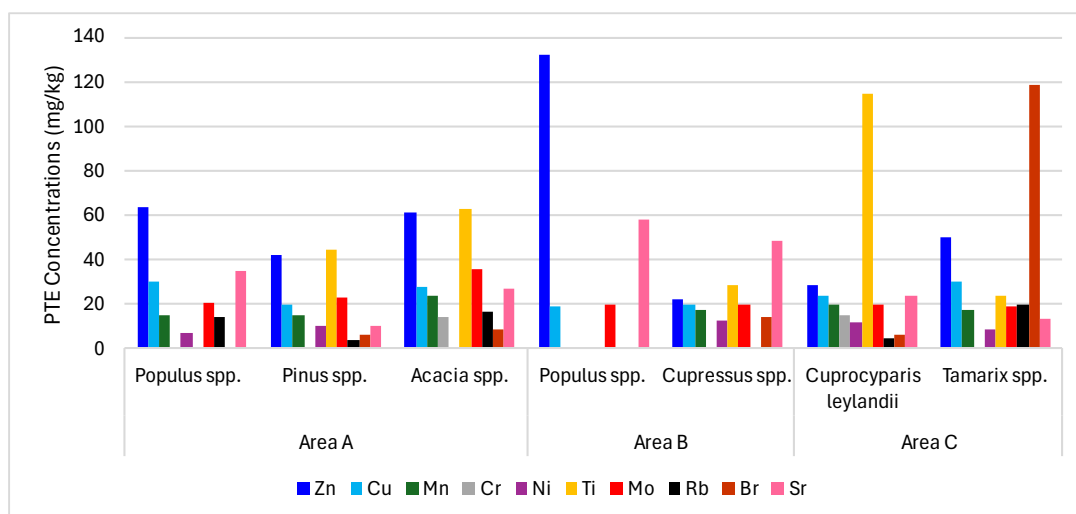


Fig. 3. Comparison of selected PTE concentrations in plant samples collected from three reforested study areas

4.3 Soil–Plant Interaction

The comparison between soil and plant concentrations indicates that the transfer of PTEs to the aerial parts of plants is limited (Figure 4). At the same time, selective uptake of essential elements occurs. This behaviour confirms their role as phytostabilisers. More specifically, in almost all cases, PTE concentrations in plant samples are lower than those in the corresponding soil samples, reinforcing this interpretation, with the sole exception of Zn in *Tamarix* from Area C, where a different trend appears. Furthermore, among all PTEs analysed in this study, Cu was detected in all six plant tissue samples, and Zn was detected in five out of six samples. These elements show the highest average plant to soil concentration ratios (i.e., 68% and 47%, respectively).

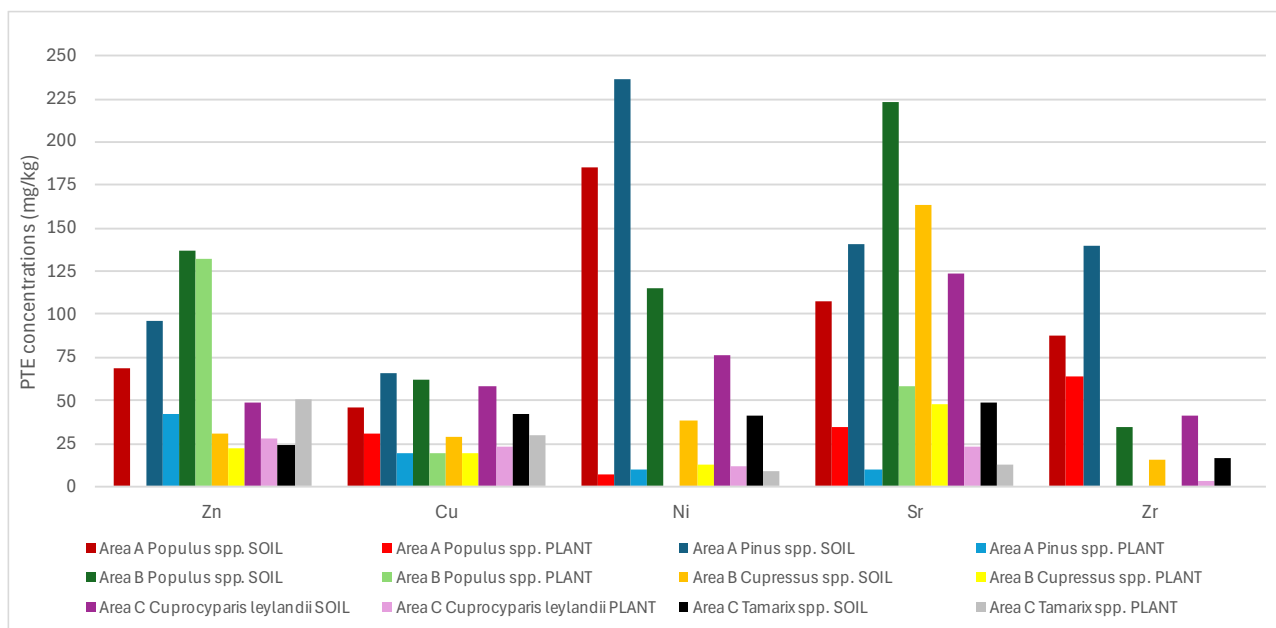


Fig. 4. Comparison of selected PTE concentrations in soil and plant samples

5. Discussion and conclusions

The results indicate that the geochemical composition of soils in the examined mine waste dumps is primarily controlled by geological factors rather than anthropogenic contamination. The elevated concentrations of major elements such as Ca, Si, Mg, and K reflect the carbonate- and silicate-rich geological background of the Ptolemaida basin and the heterogeneous nature of the deposited materials.

The slightly elevated Cr and Ni concentrations observed in Area A are closely associated with increased levels of Si, Al, Fe, and Mn and reduced Ca, suggesting the presence of silicate- and clay-rich waste materials distinct from the dominant calcareous lithologies. Similar geochemical signatures have been reported in overburden materials and clays of the wider Western Macedonia region, where Cr, in particular, exhibits relatively high enrichment factors [18] and high values in other geoenvironmental indices [19]. In addition, hydrogeochemical studies showed that Cr occurrence in the region is strongly influenced by the ultramafic environment and Mn oxides, which promote Cr release and redox transformations that affect its mobility [20]. These findings support a predominantly geogenic origin for the observed PTE concentrations.

Despite local variations in total concentrations, all measured PTEs remain below or near established environmental threshold values, indicating a generally low level of contamination. More importantly, the environmental significance of these concentrations is mitigated by their limited mobility. Previous studies comparing natural and reclaimed soils in the Ptolemais–Amynteon area have shown that the water-soluble fraction of PTEs remains low and similar between soil types, despite differences in total concentration [14]. This behaviour can be attributed to the alkaline conditions that prevail in the study area, which favour PTE immobilisation through adsorption onto mineral surfaces and incorporation into stable mineral phases.

In this context, although lignite and associated fly ash materials may exhibit considerable geochemical variability and locally elevated PTE concentrations, their contribution to PTE mobility in reclaimed soils is of secondary importance [10, 19]. Alkaline pH conditions and the mineralogical characteristics of the substrates significantly limit the dissolution and transfer of these elements to groundwater.

The analysis of plant tissues further supports the limited mobility of PTEs within the soil-plant system. The studied species exhibit low uptake and restricted translocation of PTEs to aerial parts, reflected by low plant-to-soil concentration ratios. At the same time, a preferential uptake of essential nutrients such as Ca and K is observed. This behaviour indicates the presence of selective uptake and exclusion mechanisms, which reduce the internal transfer of PTEs. Selective uptake patterns are controlled by geochemical processes in the plant rhizosphere, such as acidification, chelation by organic acids, and binding to root cell walls; these processes immobilize PTEs in the root zone and support nutrient uptake [21].

The absence of significant PTEs accumulation in above-ground biomass confirms that the examined species do not exhibit hyperaccumulator characteristics and are therefore unsuitable for phytomining applications. Instead, their functional role is clearly aligned with phytostabilisation processes. By limiting PTE mobility and contributing to the formation of a stable vegetation cover, these species enhance soil stabilisation, reduce erosion, and prevent the dispersion of particulate matter.

From a land reclamation perspective, the successful establishment of vegetation in these substrates represents a key factor for ecosystem recovery. The studied species demonstrate a high degree of adaptability to low-fertility, heterogeneous mine waste materials and are capable of supporting long-term ecological restoration without increasing environmental risk.

Overall, the findings of this study demonstrate that mine waste soils in the Ptolemaida basin do not have significant contamination but instead exhibit geochemically controlled variability. Alkaline soil conditions, low PTE mobility, and the stabilizing role of vegetation create a system where environmental risks are minimised. Consequently, the use of the examined tree species can be considered a suitable and sustainable strategy for the reclamation and stabilization of lignite mine waste dumps in Western Macedonia.

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