

Phytomining potential of naturally colonising vegetation on coal colliery spoil heaps in South Yorkshire, United Kingdom and Upper Silesia, Poland

Darragh Doyle · Leszek Szojda · Uche Onwukwe · Lorna Anguilano

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Abstract

The environmental legacy of coal mining is characterised by the widespread accumulation of spoil heaps enriched with elements, representing both a persistent ecological liability and an underutilised secondary resource. Phytomining has emerged as a promising sustainable strategy for the recovery of valuable metals from such substrates while simultaneously facilitating environmental remediation. This study evaluates the phytomining potential of two legacy coal colliery spoil heaps located at Barnsley Main (South Yorkshire, United Kingdom) and Kopalnia Węgla Kamiennego (KWK) Dębieńsko (Upper Silesia, Poland). Specific and naturally colonising species were sampled and analysed using X-ray fluorescence (XRF) spectrometry to quantify elemental accumulation within stem and leaf tissues. The results reveal pronounced inter site variability in both species composition and metal uptake capacity. Barnsley Main exhibited elevated concentrations of economically significant metals, particularly Zinc (Zn) and Copper (Cu), with *Jacobaea vulgaris* and *Leucanthemum vulgare* demonstrating notable accumulation potential. In contrast, KWK Dębieńsko displayed greater colonial floristic diversity with more spatially distributed, moderate accumulation across multiple taxa. Climatic variability between sites further influences metal mobility and bioavailability, thereby affecting uptake dynamics. Collectively, these findings underscore the viability of coal colliery spoil heaps as substrates for phytomining, while highlighting the importance of site specific environmental and biological factors in determining operational feasibility. The study contributes to the advancements of phytomining as an integrated approach to resource recovery and ecological restoration in post-industrial landscapes.

Keywords Colliery spoil deposits · Metal bioavailability · Heavy metal accumulation · Phytomining · Environmental remediation

1 Introduction

Colliery spoil deposits are persistent environmental legacies of coal extraction and may remain environmentally active for decades after mining has ceased. Their heterogeneous composition and exposure to weathering can create adverse physiochemical conditions for vegetation establishment, including nutrient deficiency, low water

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retention and where pyrite is present, acidification and associated metal mobilisation. Consequently, weathering of coal spoil can influence soil chemistry and the quality of adjacent terrestrial ecosystems. Research on hard coal spoil heaps in the Silesian Uplands of southern Poland, for example, has identified unfavourable substrate texture, low water retention, nutrient availability, organic matter and other abiotic constraints that influence spontaneous vegetation succession [1].

Conventional remediation of mine impacted land can involve substantial engineering intervention, whereas phytoremediation provides an in situ approach based on the capacity of plants to tolerate, immobilise or extract contaminants. Phytomining is a more specific application in which plants are used to produce a harvestable biomass enriched in a target metal, after which the biomass is processed to recover the accumulated elements. Thus, phytomining differs from phytoremediation in its explicit emphasis on the recovery of economically valuable elements. Importantly, successful phytomining depends not only on tissue metal concentration but also on biomass production and the resulting total metal yield [2].

Although phytomining has been investigated extensively for metal rich soils and metalliferous mine wastes, its application to legacy coal colliery spoil remains comparatively less developed. Coal spoil provides a challenging environment for plant establishment because its physical and chemical characteristics can vary substantially between sites and even within individual spoil heaps. Nevertheless, spontaneous vegetation succession demonstrates that certain plant taxa can establish under these conditions. Research on hard coal spoil heaps has shown that spontaneous succession can occur on carboniferous gangue despite severe abiotic constraints [3].

The present study therefore evaluates the phytomining potential of naturally established vegetation on two legacy coal spoil heaps in South Yorkshire, UK and Upper Silesia, Poland. Particular attention is given to species specific elemental accumulation and the extent to which metals are concentrated in above ground tissues. X-ray fluorescence (XRF) analysis is used to compare elemental concentrations among species and between sites. This approach provides an initial screening of candidate plants; however, tissue concentration alone cannot demonstrate phytomining potential, which ultimately requires consideration of biomass production, metal accumulation and translocation [4].

1.1 Coal colliery spoil heaps as substrates for phytomining and metal recovery

Coal spoil is a heterogeneous anthropogenic substrate generated during coal extraction and processing and commonly contains mixtures of shale, sandstone, claystone, siltstone and residual coal material. Its properties may differ considerably from those of developed agricultural soils. Research on three un-reclaimed hard coal spoil heaps in the Silesian Uplands of Poland found predominantly claystone and siltstone materials with additional sandstone, conglomerate, coal shale and coal, together with high surface temperatures. Such properties impose substantial constraints on plant establishment and growth [1].

The environmental behaviour of metals in coal spoil is determined not simply by total elemental concentrations but also by the chemical and physical properties of the substrate. Soil pH, Sulphur and Iron concentrations, for example, can strongly influence vegetation development and the environmental condition of coal gangue substrates. Research conducted on abandoned coal gangue piles in Guizhou, China, found substantial differences in soil pH, Sulphur and Iron between coal gangue sites and less disturbed reference areas, the authors identified excess Sulphur, Iron and associated soil acidification as important drivers of changes in vegetation composition [5].

Natural colonisation of coal spoil demonstrates that plant communities are strongly filtered by the physiochemical conditions of the substrate. Studies of hard coal spoil heaps have documented spontaneous vegetation succession and examined dominant species including *Calamagrostis epigejos*, *Poa compressa*, *Daucus carota* and *Tussilago farfara*. These findings demonstrate that persistent species on coal spoil are not necessarily classical hyperaccumulators, rather, they may possess combinations of stress tolerance, competitive ability and biomass production characteristics that allow them to persist under harsh post mining conditions [6].

The distinction between plant survival, metal accumulation and phytomining is particularly important. A species may tolerate contaminated spoil while restricting metals predominantly to its roots, making it potentially useful for phytostabilisation rather than metal extraction. Conversely, a species that translocates metals into stems have greater phytoextraction potential, but low biomass can limit the total amount of metal recovered. Field experiments with Nickel hyperaccumulators demonstrate this trade off, *Alyssum bertolonii* produced substantially greater biomass following fertilisation without a significant reduction in Nickel concentration, while *Berkheya coddii* produced still greater biomass and consequently a high total Nickel yield despite having a lower tissue concentration [4].

1.2 Diversity and metal accumulation potential of plants

The state of the art literature indicates that metal accumulation occurs across a wide range of plant taxa, but recognised hyperaccumulators are not evenly distributed among plant families. *Brassicaceae* has played a particularly important role in phytomining research, including *Alyssum* and related Nickel hyperaccumulating taxa, while species from *Asteraceae* and other families have also demonstrated substantial metal accumulation. Recent research indicates that Nickel phytomining is the most advanced application commercially, whereas phytomining of other elements remains at earlier stages of development [7].

The relevance of *Poaceae*, *Asteraceae* and *Fabaceae* to coal spoil phytoremediation arises partly from their ecological characteristics rather than from hyperaccumulation alone. Research of coal mine vegetation in Gansu, China, identified *Asteraceae* and *Poaceae* among the principal plant groups associated with coal mining environments and demonstrated differences among native species in their capacity to enrich and tolerate heavy metals. Similarly, research on post coal mining spoil heaps in Poland has shown that grass and forb species can become important components of naturally developing vegetation communities [8].

The importance of plant family should therefore be considered alongside functional traits such as growth form, life history, biomass productivity, stress tolerance and root development. In coal gangue environments, species capable of rapid establishment and continued growth under nutrient limitation and metal stress may be more useful for field scale remediation than species exhibiting exceptionally high tissue concentrations but poor biomass production. A recent study of dominant plants on coal gangue dumps demonstrated species specific differences in heavy metal enrichment and translocation, showing that the ecological suitability of a candidate species cannot be inferred from taxonomy alone [9].

1.2.1 Botanical and functional characteristics

Several species reported from coal spoil and mine waste environments are common ruderal or disturbance associated plants. Their occurrence is significant because post mining substrates represent highly disturbed environments in which rapid colonisation, tolerance of nutrient limitation and persistence under physical stress can determine which species become established. Research on coal gangue dumps has demonstrated that vegetation communities can differ substantially in species composition according to the physiochemical condition of the substrate, while studies of post coal mining spoil heaps have similarly identified distinct plant communities associated with different dominant species [5].

Poaceae may be particularly relevant to remediation of coal spoil because grasses can form persistent vegetation cover and contribute substantial biomass. Research on post coal mining spoil heaps has identified *Calamagrostis epigejos* and *Poa compressa* among dominant species and has demonstrated their influence on vegetation and substrate characteristics. The significance of grasses for phytomining should nevertheless be assessed on the base of metal concentration, biomass and translocation rather than their presence alone [6].

1.2.2 Metal accumulation, bioaccumulation factor and translocation factor

Metal accumulation and translocation provide more informative measures of phytoremediation potential than plant occurrence alone. The bioaccumulation factor (BAF) can be used to compare metal concentrations in plant tissues with those in the associated substrate, whereas the translocation factor (TF) compares metal concentrations in stems with those in roots. A recent field investigation of plants growing directly on coal gangue dumps quantified both parameters and found substantial species and elements species differences. For example, *Alnus nepalensis* showed strong translocation of Zinc and Lead, whereas *Artemisia caruifolia* exhibited comparatively strong Cadmium enrichment [9].

The distinction between root accumulation and stem accumulation is essential when assessing phytomining potential. Metals concentrated predominantly in roots are less readily recovered through harvesting of above ground biomass, whereas metals efficiently transported to stems are more accessible for subsequent processing. Experimental research on the hyperaccumulator *Spergularia rubra*, for example, found that Zinc accumulated strongly in stems whereas Lead was predominantly retained in roots, demonstrating that accumulation and translocation can differ substantially between elements within the same plant [10].

High tissue concentration alone is therefore insufficient to establish phytomining potential. The total metal recovered is determined by the interaction between biomass yield and metal concentration, while processing efficiency also depends on the chemical composition of the harvested biomass. Field phytomining experiments with *Alyssum bertolonii* and *Berkheya coddii* demonstrated that differences in biomass production can substantially influence total metal yield, while subsequent processing experiments showed that mineral composition of the biomass can affect the quality of the resulting metal-rich bio-ore [11].

1.2.3 Physiochemical conditions governing accumulation

The physiochemical characteristics of coal spoil can strongly influence both plant establishment and metal uptake. Research on coal gangue piles has demonstrated relationships between soil pH, Sulphur and Iron concentrations and plant community composition. In Guizhou, for example, coal gangue sites exhibited lower pH and higher Sulphur and Iron concentrations than less disturbed reference sites, and these changes were associated with reduced plant diversity and shifts in plant vegetation composition [5].

Metal uptake is consequently site and element specific. A field study of native plants growing around coal mining areas in Gansu, China, assessed soil contamination and plant enrichment and demonstrated differences among species in their capacity to accumulate heavy metals. Similarly, research on coal gangue dumps in Yunnan found species specific differences in both enrichment and translocation. These studies demonstrate why candidate phytomining species should be evaluated under the actual physiochemical conditions of the target spoil rather than selected solely from concentration data obtained at unrelated sites [8].

1.2.4 Implications for phytomining

The state of the art therefore indicates that successful phytomining requires a combination of biological, ecological and geochemical characteristics rather than the simple identification of plants containing elevated metal concentrations. The ideal candidate should tolerate the physiochemical constraints of the spoil, establish naturally or with minimal intervention, produce substantial harvestable biomass, accumulate the target element at elevated concentrations and efficiently translocate it into above ground tissues.

Accordingly, Table 1 should be interpreted as a screening dataset of plant taxa reported to occur on, or accumulate elements from, coal spoil and related mine wastes, rather than as a definitive list of established phytomining species. The table provides an initial comparison of botanical identity, geographic occurrence and reported target elemental accumulation, but the available literature does not justify ranking these species solely on tissue

Table 1 Selected Plant Species Reported from Coal Spoil and Mine Impacted Substrates and their Potential Relevance to Phytomining/Phytoremediation

Species	Significant elements	Country	References
<i>Medicago falcata</i>	Cu, Cr, Cd, Pb, Zn, Ni, Sb	China	[12–14]
<i>Conyza canadensis</i>			
<i>Eleusine indica</i>			
<i>Setaria viridis</i>			
<i>Cyperus eragrostis</i>			
<i>Cirsium japonicum</i>			
<i>Artemisia annua</i>			
<i>Baptisia australis</i>			
<i>Loropetalum chinense</i>			
<i>Artemisia vulgaris</i>			
<i>Miscanthus sinensis</i>			
<i>Bidens alba</i>			
<i>Boehmeria nivea</i>			
<i>Cardamine concatenata</i>			
<i>Dysphania ambrosioides</i>	Cu, Cr, Cd, Pb, Ni	Pakistan	[15]
<i>Sonchus asper</i>			
<i>Amaranthus spinosus</i>			
<i>Dodonaea viscosa</i>			
<i>Plantago ovata</i>	Cd, Pb, Zn, Hg	Ecuador	[16]
<i>Erato sodiroi</i>			
<i>Miconia laevigata</i>			

concentration. A more rigorous evaluation requires consideration of biomass, BAF, TF, substrate chemistry, plant growth form, life history and the proportion of total plant metal located in harvestable tissue.

The Chinese coal gangue study underlying several species in Table 1, is particularly useful because it directly investigated plant species growing around a coal gangue dump and reported biomass for species including *Conyza canadensis*, *Cirsium japonicum*, *Eleusine indica*, *Setaria viridis* and *Medicago falcata*. This type of dataset is considerably informative for phytomining assessment than concentration data alone because biomass and tissue concentration can be considered together.

Overall, the literature indicates that the most frequently encountered plant groups on coal and mine spoils are not necessarily the same as the botanical groups containing the best established hyperaccumulators. *Poaceae*, *Asteraceae* and *Fabaceae* are repeatedly associated with natural colonisation and revegetation of mine wastes, whereas *Brassicaceae* contains some of the best characterised metal hyperaccumulators and has played a major role in the development of phytomining, particularly for Nickel. This distinction provides an important conceptual framework for the present investigation.

The comparison of the two legacy coal spoil heaps in South Yorkshire and Upper Silesia is therefore intended to address this gap by examining whether naturally established plants exhibit consistent patterns of elemental accumulation across contrasting sites. Such a comparison is important because the phytomining potential of species is unlikely to be an intrinsic property independent of its environment, rather, it emerges from the interaction between plant physiology, species traits and the physiochemical characteristics of the substrate. The resulting evidence can help distinguish species with genuine potential for future phytomining from those whose principal value lies in phytostabilisation, ecological succession or erosion control.

2 Methodology

2.1 Study site selection

Two legacy coal colliery spoil sites were selected to investigate the phytomining potential of post mining substrates under contrasting environmental, geological and geochemical conditions. The purpose of selecting two geographically separated sites was not to assume that the spoil heaps were equivalent, but rather to examine

whether plant establishment and elemental accumulation observed in one coal mining landscape were also evident under a different set of environmental and substrate conditions. Such a comparative approach is particularly relevant to phytomining because metal availability, plant establishment and elemental uptake are influenced by the physiochemical characteristics of mine wastes, including substrate morphology, nutrient status, organic matter, weathering history and moisture availability. Research on coal mine spoil has demonstrated substantial variation in substrate properties and vegetation development even among spoil heaps within the same mining region, emphasising the importance of considering local environmental conditions when interpreting plant metal relationships.

Site selection was therefore based on a combination of ecological, historical and practical criteria. Both locations contained extensive legacy coal spoil deposits that had remained exposed to prolonged weathering and natural or seminatural vegetation colonisation. The presence of established vegetation was an important criterion because the study specifically sought to investigate naturally occurring plants rather than experimentally introduced phytoremediation crops. This approach allowed species capable of establishing and maintaining growth under the prevailing physiochemical conditions of each spoil heap to be assessed. Safe and practicable access was also required to permit systematic sampling without substantial disturbance to the established vegetation or spoil surface.

The first study site was the former Barnsley Main Colliery (see Fig. 1) in South Yorkshire, United Kingdom (53.55315386642625, -1.45142914692534). The site was selected because it represents a legacy coal mining landscape in the South Yorkshire coalfield containing substantial anthropogenically deposited spoil material that has been exposed to prolonged environmental weathering. The historical development of Barnsley Main and its associated spoil landscape forms part of the wider industrial history of the South Yorkshire coalfield. The prolonged exposure of the soil provides an opportunity to investigate plant communities that have established under post mining conditions without assuming that the material has the same geochemical characteristics as recently generated coal waste. The site therefore represents a UK example of long term ecological development on legacy colliery spoil.

The second site was the former Kopalnia Węgla Kamiennego (KWK) Dębieńsko spoil complex (see Fig. 1) in Czerwionka-Leszczyny, Upper Silesia, Poland (50.158144, 18.677301). Dębieńsko provides a particularly valuable contrasting case because the spoil complex is considerably larger and has a documented history of coal waste deposition, subsequent reclamation and secondary use. The former mine deposited more than 37 million tonnes of waste rock and tailings over an area of approximately 140 ha, including conical heaps, a large flat heap and settling ponds. The deposited materials included waste rock and coal preparation residues, meaning that the spoil represent a heterogeneous mixture rather than a uniform geological substrate.

The mineralogical and environmental characteristics of the Dębieńsko spoil further demonstrate why the site should be regarded as a contrasting case study rather than a direct replicate of the Barnsley Main site. Investigations of post mining heaps in the Silesian region have identified clayey shales containing minerals such as kaolinite and illite, together with carboniferous sandstone, claystone and residual hard coal. The Dębieńsko spoil landscape has also undergone erosion, denudation and spontaneous vegetation deployment, while historical investigations

Fig. 1 Geospatial Map of The Sampling Locations [17]. **A** Barnsley Main Colliery, South Yorkshire, United Kingdom. **B** KWK Dębieńsko, Upper Silesia, Poland



have reported pyrite bearing material and thermal activity within some coal waste deposits. These characteristics can influence weathering processes, substrate chemistry and ultimately the availability of elements to plants.

The selection of Barnsley Main and Dębieńsko therefore represents a comparative, rather than controlled, study design. The sites differ in geographical position, geological setting, climatic conditions, spoil composition, mining history, waste management practices, degree of weathering and subsequent land management. These differences were not considered experimental disadvantages, instead they constitute an important component of the research question. The comparison was intended to determine whether elemental accumulation by naturally established vegetation is consistent across contrasting legacy coal spoil environments or whether observed accumulation is strongly site specific.

A further limitation concerns the availability of equivalent plant species at both locations. Because the study investigated naturally established vegetation, it was not possible to impose an identical species composition across the two sites without introducing an experimental planting regime that would have changed the ecological basis of the study. Consequently, not all plant species sampled at Barnsley Main were present at Dębieńsko, and vice versa. This means that direct comparison of absolute elemental concentrations between different species across the two sites must be interpreted cautiously, because differences may reflect both species specific uptake characteristics and differences in substrate conditions. Species level comparisons are therefore primarily used to identify elemental accumulation within each site, while inter site comparisons are interpreted in terms of overall elemental behaviours and the interaction between plant identity and local environmental conditions.

Where taxonomically comparable species occurred at both sites, their elemental concentrations provided a more informative basis for assessing the influence of site conditions. Conversely, species occurring at only one site are interpreted as evidence of the ecological filtering and plant selection processes operating under the site's particular conditions rather than as direct experimental equivalents. This distinction is consistent with research demonstrating that different plant species can exhibit markedly different metal uptake and translocation behaviour even when growing on the same contaminated substrate.

In subsequent analyses, the contrasting environmental and substrate characteristics of Barnsley Main and Dębieńsko are treated as important contextual variables rather than assuming that the sites represent equivalent experimental conditions. This approach enables the study to assess the extent to which naturally occurring vegetation demonstrates potentially useful elemental accumulation across different legacy coal spoil environments, while explicitly recognising the limitations imposed by differences in geology, spoil composition, mining history and plant community composition.

2.2 Field sampling and species identification

Field sampling focused on specific and naturally established colonising vegetation growing directly on spoil heap substrates, as such species are more likely to exhibit tolerance to metal stress and potential hyperaccumulation traits. Plant tissues, specifically the leaf material and stem were pruned for analysis due to their roles in metal uptake, translocation and accumulation.

Cuttings/Samples were collected using sterilised secateurs (Stihl Bypass PG 10) to minimise cross contamination between specimens. Each Sample was immediately placed into ventilated labelled storage bags (VWR LDPE Zipper), with identifiers including site location, date and species classification to ensure traceability throughout the analytical workflow.

Species identification was conducted using a multi method approach to maximise taxonomic accuracy. This included field based morphological assessment, consultation of authoritative botanical literature (Royal Horticultural Society) and verification using digital plant identification tools (PlantSnap and PictureThis). Cross referencing between these methods reduced the likelihood of misidentification, which is critical for interpreting species specific accumulation behaviour.

2.3 Sample preparation

Upon transport to the laboratory, all samples were catalogued and subjected to controlled preparation procedures to ensure analytical consistency. The above ground plant material was first washed thoroughly with deionised water to remove adhering soil particles, dust and other surface contaminants that could influence subsequent elemental analysis. Leaves were gently rinsed under a continuous flow of deionised water, with care taken to avoid excessive handling or damage to the leaf tissue. The washed material was then placed on clean, lint free laboratory paper and allowed to drain and air dry briefly to remove excess surface water. Following washing, the plant material was oven dried at 65°C for 24 h to remove residual moisture while minimising the risk of thermal degradation or volatilisation of target elements. Drying was continued until a constant dry weight was achieved, providing a consistent basis for expressing elemental concentration on a dry mass basis.

Following drying, samples were homogenised by grinding them into a fine powder using a pestle and mortar, a critical step to reduce intra sample variability and ensure that subsamples used for analysis are representative of the whole above ground plant tissue. The production of a fine, homogenous powder also improved sample uniformity and contributed to greater analytical precision in subsequent spectrometric measurements.

2.4 Elemental analysis by energy-dispersive X-ray fluorescence (EDXRF)

Elemental analysis was conducted using an energy-dispersive X-ray fluorescence (EDXRF) spectrometer (Rigaku NEX DE XRF), a non-invasive/non-destructive technique widely employed for multi-element analysis of environmental and biological samples. Prior to analysis, powdered samples were weighed and placed into sterilised sample holders, using a thin film (Cole-Parmer 3520 polypropylene) to create a uniform and stable analytical surface while maintaining X-ray attenuation and reducing cross contamination. The NEX DE is equipped with a silicon drift detector (SDD) and an X-ray tube capable of operating up to 60 kV and 12 W. Quantification was performed using the instruments calibration (MCA-R2128) within the Rigaku QuantEZ software, ensuring accuracy and reproducibility of measurements. The operating conditions were 60 kV, 12 W and a count time of 100 s per sample. The detector was a SDD, and spectra were processed using QuantEZ version 6.08. EDXRF analysis enabled the rapid quantification of a broad range of elements, including trace elements relevant to phytomining (*Ti*, *Mn*, *Ni*, *Cu*, *Zn*) without the need for extensive chemical digestion, making it particularly suitable for high throughput screening of plant material.

The XRF analysis focused on determining the concentration of metal accumulated within plant tissues, providing an indirect measure of metal bioavailability within the spoil heap substrate.

2.5 Data processing and interpretation

Following data acquisition, energy-dispersive X-ray fluorescence (EDXRF) spectra were processed using the instrument software to obtain quantitative elemental concentrations. Data quality was assessed by checking the measurements for consistency and reviewing the spectra for irregular peak profiles, excessive background and values inconsistent with the analytical range. Measurements affected by analytical anomalies were re-examined and, where necessary, repeated. Elemental concentrations were retained only when the corresponding signal met the established analytical criteria and was above the method reporting limit.

The processed data were systematically organised into tabulated formats to enable comparison across species and sites. This facilitated the identification of potential hyperaccumulator species and the valuation of spatial variability in metal uptake. The resulting dataset formed the basis for subsequent analysis, interpretation and discussion regarding the feasibility of phytomining in coal colliery spoil heap environments.

3 Results and discussion

3.1 Elemental accumulation patterns in Barnsley Main Colliery, South Yorkshire, UK

Energy-dispersive X-ray fluorescence (EDXRF) analysis of the above ground plant material from Barnsley Main colliery, demonstrated substantial interspecific and temporal variation in elemental concentrations. Among the species analysed, *Leucanthemum vulgare* and *Jacobaea vulgaris* generally exhibited the highest concentrations of several elements of interest, particularly *Zn*, *Cu* and *Mn*. The highest *Zn* concentration recorded for *L. vulgare* was 497 mg kg⁻¹ in March 2024, while *J. vulgaris* reached 903 mg kg⁻¹ *Zn* in November 2023 (see Table 2). These results demonstrate that both species were capable of accumulating measurable concentrations of *Zn* under the conditions prevailing at the site.

However, the observed foliar concentrations should be interpreted as evidence of elemental accumulation rather than confirmed phytomining or hyperaccumulation. Classification of a plant as a hyperaccumulator requires consideration of the concentration of the element in the plant relative to its substrate, together with its ability to

Table 2 Elemental Concentration (mg kg⁻¹) of Species from Barnsley Main Colliery Spoil Heap (UK) Quantified via EDXRF Spectrometry

Species (Folium Concentration)	Elements of Interest- Barnsley Main Coal Colliery South Yorkshire, United Kingdom (Milligrams per Kilogram mg kg ⁻¹)						
	Ti	Mn	Ni	Cu	Zn	Al	Fe
July 2024							
<i>Leucanthemum vulgare</i>	—	47	10	16	175	5822	229
<i>Agrostis stolonifera</i>	—	60	14	11	148	—	72
<i>Jacobaea vulgaris</i>	—	11	5	10	167	—	57
<i>Zea mays</i>	—	18	7	10	54	—	49
June 2024							
<i>Leucanthemum vulgare</i>	36	93	17	28	470	—	213
<i>Jacobaea vulgaris</i>	—	34	11	22	222	—	91
March 2024							
<i>Leucanthemum vulgare</i>	297	152	29	74	497	21,646	2322
<i>Jacobaea vulgaris</i>	127	157	21	97	493	38,529	11,960
February 2024							
<i>Leucanthemum vulgare</i>	158	56	25	58	205	12,226	1287
<i>Agrostis stolonifera</i>	157	181	21	58	264	16,777	1588
<i>Jacobaea vulgaris</i>	161	61	21	48	244	14,766	1399
November 2023							
<i>Leucanthemum vulgare</i>	60	41	12	23	133	889	895
<i>Agrostis stolonifera</i>	32	99	25	18	212	6986	246
<i>Jacobaea vulgaris</i>	178	104	75	68	903	15,719	1266
August 2023							
<i>Agrostis stolonifera</i>	31	—	13	16	78	—	—
<i>Jacobaea vulgaris</i>	—	—	69	31	220	—	—
<i>Zea mays</i>	—	—	10	10	29	—	—
July 2023							
<i>Agrostis Stolonifera</i>	8	—	4	6	59	—	—
<i>Jacobaea vulgaris</i>	1	—	3	3	17	—	—
<i>Zea mays</i>	—	—	7	12	57	—	—
June 2023							
<i>Agrostis stolonifera</i>	—	—	2	5	44	—	—
<i>Jacobaea vulgaris</i>	497	—	9	57	402	—	—
<i>Zea mays</i>	—	—	8	13	98	—	—

“—” indicates data not available

translocate the element from roots to harvestable above ground biomass. Bioaccumulation (BAF) and translocation factors (TF) are therefore important parameters when assessing phytoextraction potential. Since substrate and root concentrations were not measured in the present study, neither the BAF nor the TF could be calculated. Consequently, the present results indicate elemental accumulation in above ground biomass, but do not demonstrate the extent to which the measured elements originated from the substrate or were translocated from root to stem [18].

Temporal variation was also apparent in the Barnsley dataset. Several of the higher concentrations occurred during November 2023 and March 2024, although the pattern was not uniform across all species or elements. For example, *L. vulgare* recorded 497 mg kg⁻¹ Zn in March 2024 compared with 113 mg kg⁻¹ in November 2023, whereas *J. vulgaris* recorded its highest Zn concentration of 903 mg kg⁻¹ in November 2023. Such variation may reflect seasonal changes in plant growth, water availability, substrate chemistry and metal mobility; however, these mechanisms cannot be established directly from the present dataset. Metal uptake is controlled by interacting factors including element speciation, soil or substrate properties and plant specific physiological characteristics [19].

The exceptionally high Al and Fe concentrations observed in several Barnsley samples are also noteworthy. *L. vulgare* contained up to 21,646 mg kg⁻¹ Al and 2322 mg kg⁻¹ Fe in March 2024, while *J. vulgaris* reached 38,529 mg kg⁻¹ Al and 11,960 mg kg⁻¹ Fe during the same sampling period (see Table 2). These concentrations indicate substantial accumulation of association Al and Fe bearing material within the analysed plant samples. Nevertheless, because roots and corresponding spoil samples were not analysed, it cannot be determined whether these values represent physiological uptake, surface associated mineral particles or a combination of both. This distinction is particularly important for plants growing directly on heterogeneous mine spoil where particulate contamination may contribute to elemental concentrations measured in above ground material [20].

From a phytomining perspective, Zn and Cu are more relevant to the present investigation than the major lithogenic elements Al and Fe. Nevertheless, concentration alone is insufficient to establish the feasibility of metal recovery. Phytomining performance depends on a combination of metal concentration, above ground biomass production, plant adaptability and the quantity of recoverable metal generated per unit area. Thus, *L. vulgare* and *J. vulgaris* can be regarded as candidate species for further investigation, rather than confirmed phytomining species.

3.2 Elemental accumulation patterns in KWK Dębieńsko, Upper Silesia, Poland

The preliminary single point screening at KWK Dębieńsko identified a comparatively diverse assemblage of spontaneously established vegetation and substantial variation in elemental concentrations among species (see Table 3). Notable concentrations included Zn in *Pimpinella anisum* (314 mg kg⁻¹), Mn in *Reynoutria japonica* (72 mg kg⁻¹), and Fe in *Lactuca sativa* (2343 mg kg⁻¹). *Tussilago farfara* also exhibited elevated Al (17465 mg kg⁻¹) and Ti (181 mg kg⁻¹).

These results demonstrate species specific differences in elemental accumulation; however, they should not be interpreted as evidence that one species is inherently more efficient in extracting metals than another. Metal accumulation is influenced by both plant traits and environmental conditions, including metal availability and physiochemical characteristics. Furthermore, the Polish dataset represents a single sampling period in April 2024. Consequently, seasonal trends and temporal stability of accumulation could not be evaluated [21].

The relatively high Al concentration recorded in *T. farfara* and Fe concentration in *L. sativa* are particularly important when interpreting the EDXRF results. As with the Barnsley samples, the absence of corresponding root and substrate measurements prevents determination of whether these elements were actively absorbed and translocated into the foliage or were partly associated with externally deposited mineral particles. Therefore, these measurements provide evidence of elemental presence in the analysed biomass but cannot independently establish substrate to plant transfer [22].

Table 3 Elemental Concentration (mg kg^{-1}) of Species from Kopalnia Węgla Kamiennego (KWK) Dębieńsko Colliery Spoil Heap (Poland) Quantified via EDXRF Spectrometry

Species (Spontaneous Vegetation Folium Concentration-April 2024)	Elements of Interest- KWK Dębieńsko Coal Colliery Upper Silesia, Poland (Milligrams per Kilogram mg kg^{-1})						
	Ti	Mn	Ni	Cu	Zn	Al	Fe
<i>Dryopteris filix-mas</i>	6	7	4	10	57	166	166
<i>Phragmites australis</i>	11	59	9	13	33	4663	173
<i>Urtica dioica</i>	34	17	8	14	58	525	523
<i>Bryophyta</i>	29	19	4	3	16	1752	325
<i>Cirsium arvense</i>	21	12	6	11	36	556	327
<i>Sonchus oleraceus</i>	—	26	8	12	20	—	133
<i>Tussilago farfara</i>	181	47	16	25	44	17,465	1084
<i>Pimpinella anisum</i>	—	24	4	6	314	3535	522
<i>Sideritis syriaca</i>	17	7	7	7	26	257	287
<i>Poaceae</i>	7	43	6	8	13	159	130
<i>Reynoutria japonica</i>	6	72	6	11	81	243	229
<i>Trifolium pannonicum</i>	5	15	5	6	110	—	97
<i>Asplenium marinum</i>	14	20	5	7	10	250	225
<i>Daucus carota</i>	84	53	10	15	23	9050	797
<i>Lactuca sativa</i>	115	53	8	8	32	2011	2343
<i>Tanacetum vulgare</i>	34	44	8	29	102	12,490	541
<i>Erigeron</i>	23	16	5	7	51	386	316
<i>Pinus sylvestris</i>	—	66	5	4	14	85	30
<i>Cakile maritima</i>	13	6	5	8	39	392	276
<i>Lupinus polyphyllus</i>	2	16	5	6	16	96	48
<i>Barbarea vulgaris</i>	15	11	8	7	37	283	167

“—” indicates data not available

The Polish results also illustrate an important limitation of comparing the two study sites. The species sampled at KWK Dębieńsko were not the same as those sampled at Barnsley Main, and the polish site was assessed at only one time point. Consequently, differences between sites cannot be attributed solely to differences in substrate geochemistry, climate or metal bioavailability. They may also reflect differences in species composition and plant specific uptake mechanisms. A robust cross site comparison would require the same plant species to be sampled at both locations under comparable phenological conditions, together with paired measurements of substrate, roots and stems.

3.3 Comparative assessment of phytomining potential

The two sites displayed contrasting patterns of elemental accumulation, with Barnsley Main producing higher maximum concentrations of several target elements, particularly *Zn* and *Cu*, whereas KWK Dębieńsko demonstrated greater taxonomic diversity among the sampled vegetation. However, these differences should be considered descriptive rather than definitive evidence that one site possess greater phytomining potential.

Direct comparison is constrained by three methodological factors, different plant species were sampled at the two sites, Barnsley was monitored over multiple sampling periods whereas KWK Dębieńsko was sampled only once, and substrate and root concentrations were not measured. Consequently, the observed differences represent the combined influence of site conditions, species composition and sampling period rather than a controlled comparison of site specific metal uptake.

In particular, the absences of substrate concentrations mean that the relative bioavailability of metals at the two sites cannot be established. Similarly, without root measurement, the extent of translocation into harvestable stems cannot be determined. BAF and TF are commonly used to distinguish effective uptake from effective root

Table 4 Comparative Climatic Conditions for South Yorkshire (UK) and Upper Silesia (Poland), Including Temperature (°C), Sunshine Duration (Hrs), Rainfall (mm) and Precipitation Frequency (Days) During the 2023/2024 Study Period [24]

Month	Temperature (°C)	Sunshine (Hrs)	Rainfall (mm)	Rain (Days)
<i>South Yorkshire, United Kingdom Annual Weather Averages 2023/24</i>				
February	4	84	64.28	7
March	6	110	60.30	7
June	14	106	77.06	8
July	16	99	88.77	10
August	16	117	78.97	9
November	7	101	74.86	8
<i>Upper Silesia, Poland Annual Weather Averages 2023/24</i>				
April	9	56	51	16

to stem transfer, and both are relevant when evaluating phytoextraction and phytomining potential. The current results therefore provide a screening level assessment of elemental concentrations in above ground biomass, rather than a completed evaluation of phytomining efficiency [22].

The relatively high *Zn* concentrations observed in *L. vulgare* and *J. vulgaris* at Barnsley nevertheless identify these species as suitable candidates for follow up investigation. Their suitability for phytomining would require confirmation through paired soil/plant analysis, root to stem measurements, biomass assessment and repeated sampling. Importantly phytomining requires not simply high tissues concentrations but sufficient harvestable biomass and an adequate metal yield per unit area [23].

3.4 Influence of climatic and environmental conditions

Seasonal climatic conditions may contribute to variation in elemental concentrations, but the present data do not permit climate to be isolated as the casual factor. At Barnsley, higher concentrations were observed during some cooler and wetter sampling periods (see Table 4), however, these responses differed among species and elements. Changes in precipitation can influence water movement and chemical mobilisation within mine spoil, while temperature and plant growth stage can alter physiological uptake. More broadly, metal bioavailability is strongly dependent on substrate properties and metal speciation rather than climatic conditions alone [19].

The climatic comparison between South Yorkshire and Upper Silesia should therefore be regarded as contextual rather than mechanistic. The UK dataset contains repeated observations across several months, whereas the Polish dataset represents April 2024 only. It is consequently not possible to establish a statistically supported relationship between rainfall, temperature and elemental uptake at the Polish site. Similarly, differences between the two locations cannot be attributed to climate independently of differences in geology, spoil composition, vegetation and sampling design.

3.5 Limitations and implications for phytomining assessment

The principal limitation of this study is that only above ground plant tissues were analysed. No paired measurements of the spoil substrate or roots were undertaken. Consequently, the study cannot determine the concentration of each element available in the substrate, the proportion taken up by the plants, or the extent to which metals were translocated from roots to stems. These limitations prevent calculation of BAF and TF and therefore preclude definitive classification of the investigated species as hyperaccumulators or phytomining species [18].

A second limitation is the lack of identical species across both sites. Because plant species differ substantially in metal uptake, tolerance, transport and sequestration mechanisms, comparisons based on different species cannot provide a direct test of site effects. Hyperaccumulating plants can possess specialised physiological mechanisms that enhance metal uptake, transport and sequestration, meaning that species identity is an important determinant of observed accumulation.

Despite these limitations, the results provide useful preliminary evidence for identifying species and elements warranting further investigation. The elevated *Zn* and *Cu* concentrations recorded in selected Barnsley species,

together with the diversity of elemental accumulation observed at KWK Dębieńsko, support the value of these sites for further phytoremediation and phytomining research. Future work should employ a standardised sampling design incorporating the same plant species at both sites, paired substrate and root analyses, substrate pH and physiochemical characterisation, replicate sampling across seasons, and measurements of above ground biomass. These data would enable calculation of BAF and TF and provide a more robust assessment of whether the observed elemental accumulation can translate into practical phytomining potential.

4 Conclusion

This study provides a comparative assessment of phytomining potential across two legacy colliery spoil heap environments, demonstrating that such substrates can function as viable systems for both metal recovery and ecological remediation. The findings reveal marked inter site variability, with Barnsley Main Colliery characterised by elevated concentration of economically valuable metals particularly *Zn* and *Cu*, concentrated within a limited but consistent number of dominant species. In contrast, KWK Dębieńsko exhibited greater colonial floristic diversity and more evenly distributed, moderate accumulation profiles across a wider range of taxa.

These contrasting patterns suggest differing operational pathways for phytomining implementation. Barnsley Main presents favourable for conditions targeted phytomining strategies, whereby high performing select species may be cultivated to maximise metal and mineral recovery efficiency. Conversely, the Polish site demonstrates greater potential for integrated phytoremediation approaches, in which diverse plant communities contribute to both stabilisation and gradual extraction of metals over extended timescales.

The influence of climatic variability further highlights the importance of environmental controls on metal mobility and plant uptake dynamics, emphasising the need for site specific optimisation in phytomining systems design. Importantly, the consistent accumulation of metals and minerals such as *Ti*, *Mn*, *Ni*, *Cu*, *Zn*, *Al* and *Fe* across both sites confirm their bioavailability within coal spoil substrates, reinforcing the conceptual viability of phytomining in these environments.

This comprehensive study advances the understanding of phytomining within post-industrial landscapes and supports its development as a sustainable, dual-purpose strategy for environmental remediation and resource recovery. Future research should aim to enhance biomass productivity, refine species selection or integrate phytomining with complimentary remediation technologies to improve scalability and economic viability.

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Author contributions D.D: Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualisation; Writing-Original draft; Review and editing. L.S: Investigation; Methodology; Resources; Validation; Writing-Review and editing. U.O: Conceptualisation; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualisation; Writing-Review and editing. L.A: Conceptualisation; Funding Acquisition; Investigation; Methodology; Project Administration; Resources; Software; Supervision; Validation; Visualisation; Writing-Review and editing.

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Data availability All data supporting the findings of this study are available within the paper.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

Plant source Plant material used in this study comprised of naturally colonising vegetation collected from two historic coal colliery spoil heaps: Barnsley Main Colliery, South Yorkshire, United Kingdom (53.55315386642625, -1.45142914692534), and Kopalnia Węgla Kamiennego (KWK) Dębieńsko, Upper Silesia, Poland (50.158144, 18.677301).

Plant guidelines Plant collection was undertaken solely for scientific research purposes from post-industrial sites in accordance with applicable institutional, local and national regulations governing field sampling. Sampling was restricted to naturally established vegetation, and reasonable care was taken to minimise disturbance to the surrounding environment.

Plant identifier Plant species used in this study were identified and verified by Darragh Doyle (Brunel University of London), using standard taxonomic keys and morphological characteristics appropriate for the flora of the United Kingdom and Poland. Species identification was undertaken prior to sample collection and processing to ensure the accurate taxonomic classification of all naturally colonising vegetation included in the study.

Herbarium name Representative voucher specimens of all wild plant species collected during this study have been deposited in the Experimental Techniques Centre (*ETC*) to ensure the long-term preservation and accessibility of the plant material.

Specimen voucher ID The corresponding voucher specimen accession numbers are as follows: Collection-Voucher ID: PHY-UK-POL-001.

Permissions to collect the plants/Plant Parts Not applicable.

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Authors and Affiliations

Darragh Doyle¹ · Leszek Szojda² · Uche Onwukwe^{3,4} · Lorna Anguilano^{3,4}

✉ Lorna Anguilano
lorna.anguilano@brunel.ac.uk; lorna@phyona.co.uk

Darragh Doyle
darragh.doyle@brunel.ac.uk

Leszek Szojda
leszek.szojda@polsl.pl

Uche Onwukwe
uche.onwukwe@brunel.ac.uk; uche@phyona.co.uk

¹ Department of Chemical Engineering, Brunel University of London, London UB8 3PH, UK

² Department of Civil Engineering, Silesian University of Technology, Gliwice 44-100, Poland

³ Experimental Techniques Centre, Brunel University of London, London UB8 3PH, UK

⁴ Phyona Limited, Lincolnshire PE9 2PF, UK