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1. Introduction

The Waste2CRM project - Determination of the potential for sourcing critical raw materials from mining wastes, and development the method for their effective recovery - is implemented within the Research Fund for Coal and Steel programme. The project addresses two closely related challenges of strategic importance for the European Union: the need to secure alternative and sustainable sources of critical raw materials (CRMs), including rare earth elements (REEs), and the need to support the transition of coal-dependent regions by transforming deposited mining wastes into potential secondary raw material resources of coal mining waste currently accumulating in heaps and backfill areas across Europe.

Critical raw materials, including rare earth elements, are essential for the development and resilience of the European economy. They are used in a wide range of strategic sectors, including renewable energy technologies, electromobility, electronics, advanced materials, defence, aerospace, digital infrastructure and industrial decarbonisation technologies. REEs are particularly important for the production of permanent magnets, batteries, catalysts, sensors and other high-performance components required for the green and digital transition. At the same time, the EU remains highly dependent on imports of many CRMs and REEs, often from a limited number of non-European suppliers. This creates potential supply risks, price volatility and strategic vulnerabilities. For this reason, the identification of secondary sources of CRMs within Europe, including mining wastes deposited in coal and lignite regions, is of major importance for strengthening raw material security, supporting circular economy strategies and reducing dependence on primary extraction outside the EU.

The inventory carried out within the Waste2CRM project confirms that coal and lignite mining wastes deposited in heaps, waste dumps and other post-mining facilities represent a widely available and spatially distributed secondary resource base in the investigated European regions. In Poland, the updated database developed includes 152 hard-coal mining waste heap sites, of which lithostratigraphic information was successfully assigned to 151 objects. In Spain, the inventory based on historical IGME data identified 141 coal waste dump sites distributed across the main former coal mining basins, including Asturias, León, Palencia, Teruel, Zaragoza, Córdoba and Seville. In Greece, the database compiled for Western Macedonia includes 16 lignite mining waste-related sites. These figures demonstrate that post-mining waste deposits are not isolated or marginal occurrences, but constitute a significant resource base that may be considered in the context of critical raw material recovery.

Coal and lignite mining activities have generated large volumes of waste materials, which have traditionally been regarded mainly as an environmental and land-management burden. However, these materials may also contain elements of economic and strategic importance, including CRMs and REEs. Their occurrence in already existing and accessible heaps is particularly important, as it creates the possibility of assessing and potentially recovering valuable elements without the need to develop new primary mining operations. In this context, the Waste2CRM project aims to evaluate the potential of selected coal and lignite mining waste deposits as secondary sources of CRMs and REEs, and to provide a scientific basis for the development of effective recovery methods. The large number of inventoried sites provides a strong justification for further geochemical, mineralogical and technological studies focused on transforming selected post-mining wastes from environmental liabilities into potential secondary raw material resources.

2. Field sampling of representative mining wastes

This report focuses exclusively on waste materials collected from deposited spoil heaps and does not include wastes originating from current mining or coal processing production streams. The investigated materials were obtained from selected sites in Poland, Spain and Greece. The sampling campaigns were designed to obtain representative material from the investigated deposits. In Poland, samples were collected from borehole profiles drilled into spoil heaps, with sampling conducted at different depths. In Spain, samples were collected from two waste heaps using a trial pit approach, whereas in Greece the sampling campaign involved drilling boreholes with continuous coring in the spoil heaps of a lignite mine in NW Macedonia (LM-GR site).

Poland

In Poland, representative samples were collected from six hard-coal mining waste heaps corresponding to selected coal lithostratigraphic units. In order to ensure that the report can be made publicly available without disclosing sensitive site-specific information, the Polish sampling locations are not identified by mine name or exact geographical location. Instead, the results for Polish samples are presented and interpreted at the level of lithostratigraphic affiliation, including the Upper Silesian Sandstone Series (USSS), the Kraków Sandstone Series (CSS) and the Paralic Series (PS). This approach enables the geochemical characteristics of the investigated materials to be discussed in a scientifically meaningful way, while maintaining confidentiality with respect to the exact origin of the Polish waste samples.

The importance of lithostratigraphic affiliation is justified by the observed geochemical differentiation between the distinguished stratigraphic series, indicating that the geological origin of the material is reflected in its chemical composition.

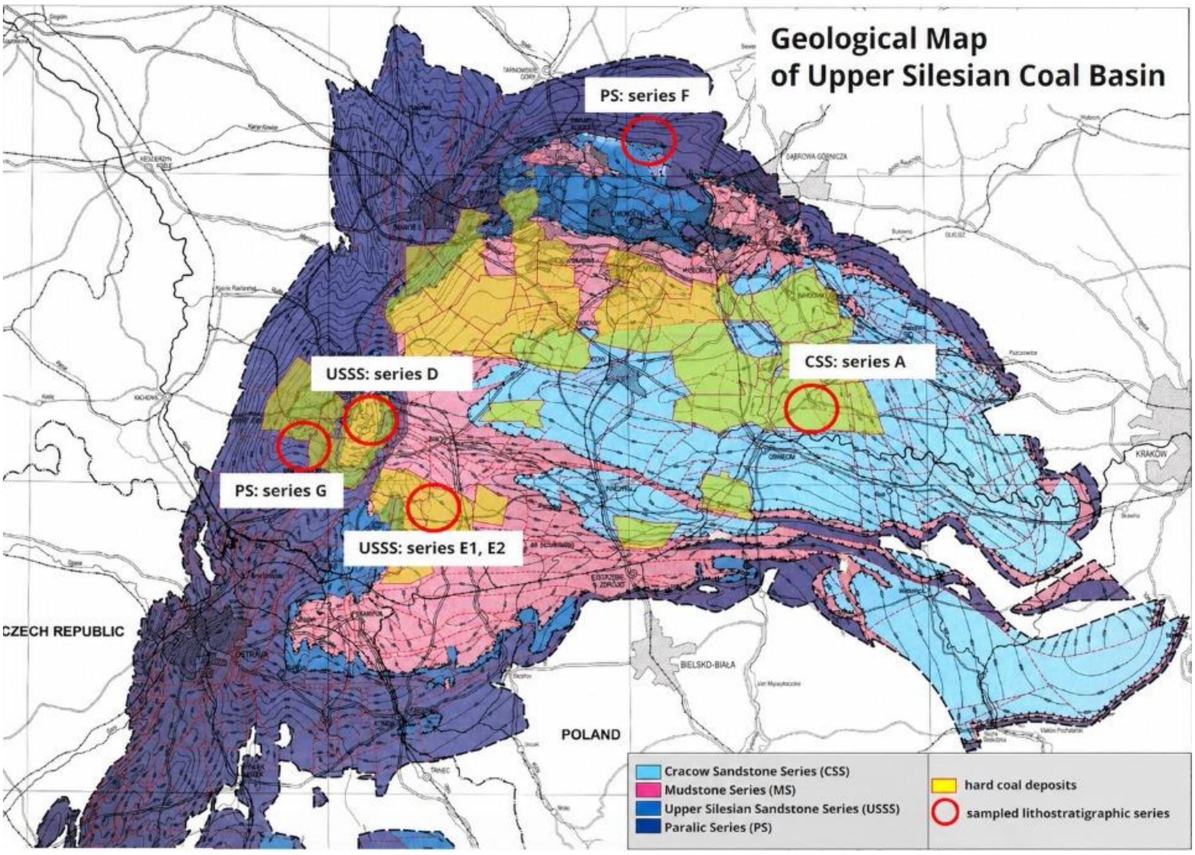

Fig. 1. Lithostratigraphic location of investigated waste heaps.

At each spoil heap, three boreholes were drilled and distributed in a way that allowed the surface of the heap to be covered as evenly as possible. The boreholes were drilled using an uncased drilling method with 130 mm auger bits. From each borehole, samples were collected along a vertical profile reaching a depth of up to 15-20 m, with sampling performed every 5 m. This approach enabled the collection of representative material from different parts and depths of each heap, allowing both horizontal and vertical variability in CRM and REE contents to be assessed.

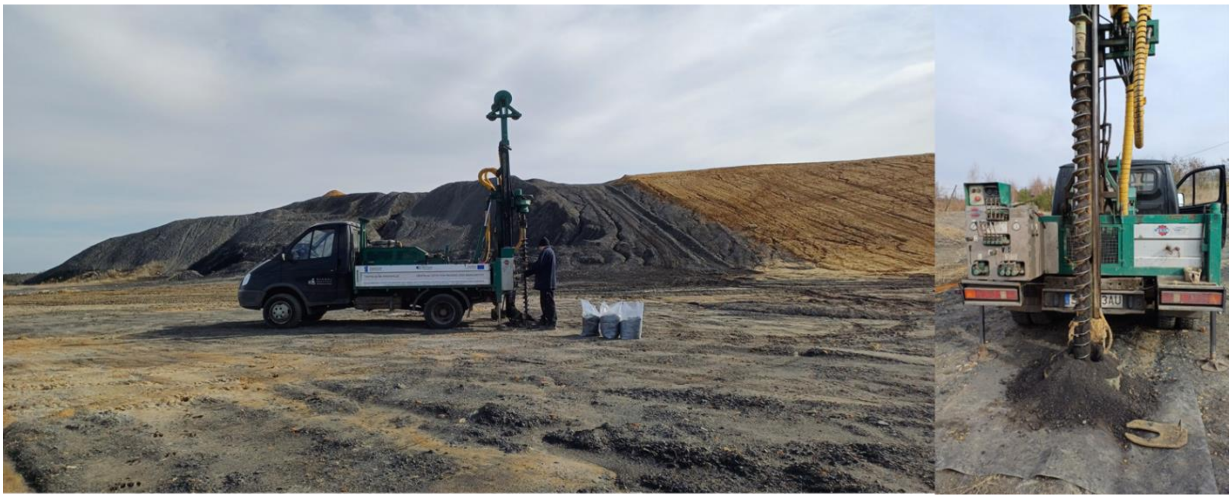

Fig. 2. Sampling on the plateau surface of the spoil heap (Poland) - drilling rig belonging to the Central Mining Institute -National Research Centre (GIG-PIB).

Spain

For the field campaign to collect samples from coal waste dumps in Spain, two dumps located at the Santa Bárbara Foundation's (FSB) facilities were selected. The Santa Bárbara Foundation is a public entity of the Castilla y León Community, located in the province of León (Ponferrada), in the northwest of the Iberian Peninsula (Figure 3).

The aim of this Foundation is to collaborate in social welfare and to promote activities aimed at fostering the knowledge and development of the work inherent to mining. Nowadays, it has strengthened and diversified its foundational aims, becoming a consolidated entity in the field of teaching and technological activities in sectors such as mining, energy, construction, and occupational safety and civil protection, among others.

With regard to the sampling methodology, 20 samples were collected from each waste heap, giving a total of 40 samples from both locations. The samples were placed in sampling bags, each weighing approximately 7 kg. Starting from the initial sampling point, subsequent samples were collected at intervals of approximately 5 m, using the trial pit method.

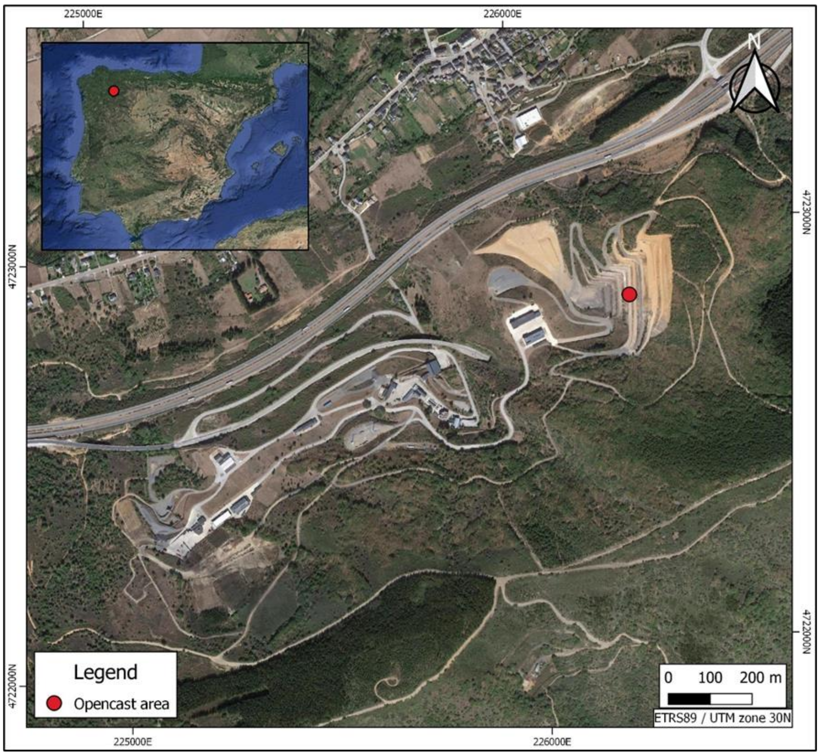

Figure 3. Santa Bárbara Foundation Mine School location.

Fig. 4. Sampling of the sample in Laciana (top photo) and El Bierzo (bottom photo) by Systra.

Greece

The Northern Waste Dump of the Greek Lignite Mine (LM-GR site), located in the area of Kozani, was selected as the sampling area (Fig. 5). The studied Lignite field is located in Western Macedonia, Northern Greece, belonging to the Pelagonian Unit of metamorphic formations, which includes crystalline rocks, mostly limestones and gneisses, as well as ophiolites and granitic intrusions (bedrock formations). The LM-GR mine area is located in the southern part of the Kozani - Servia basin. This lignite-bearing basin is part of the wider lignite-bearing basin of Florina-Amyndion-Ptolemaida-Kozani-Servia-Elassona, which is part of the large tectonic trench of Western Macedonia, > 120 km long, extending from Monastiri (Northern Macedonia) to Elassona, south of the Aliakmonas River.

The waste thickness at this site ranges from 80 to 100 m. The field sampling campaign was carried out in the summer of 2025 and included the drilling of two boreholes with continuous coring, using a core diameter of 80 mm.

Fig. 5. Location and borehole profile at LM-GR site.

Fig. 6. Lignite mine waste sampling - LM-GR

All collected samples were subjected to the physicochemical, geochemical and mineralogical characterisation, with particular emphasis on determining the contents of selected critical raw materials. A set of complementary analytical methods was applied, enabling assessment of the chemical and mineral composition as well as the morphological characteristics of the investigated materials. Selected results of the conducted analyses are presented in section 3.

3. Analysis of the contents of selected elements in coal mining waste collected from heaps in Poland, Spain and Greece.

This chapter discusses the research results obtained for selected heaps of hard coal and lignite mining waste. Table 1 summarizes the elements determined in the investigated samples. The concentrations of selected elements were analysed using two different sample digestion procedures: lithium borate fusion and modified aqua regia digestion, prepared as a 1:1:1 mixture of HNO_3, HCl and H_2O. The use of these complementary digestion methods enabled the determination of elemental contents under different extraction conditions and supported a broader assessment of the chemical composition of the analysed material.

Table 1. Elements whose contents were determined in the investigated coal mining waste samples.

Elements	Sample preparation method
Major oxides: SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, MnO, Cr_2O_3	A
Mo, Cu, Pb, Zn, Ag, Mn, Fe, As, Au, Cd, Sb, Bi, Ca, P, Cr, Mg, Ti, B, Al, Na, K, Tl, S, Hg, Se, Te, Ge, In, Re, Li, Pd, Pt	B
REE and Ba, Ni, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Zr,	A and B (2 methods)
C_{tot}, S_{tot}	-

REE: Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu
A – Fusion with lithium tetraborate; B – digestion in modified Aqua Regia (1:1:1 HNO_3:HCl:H_2O).

Platinum group metals are classified as critical raw materials. Within the scope of this work, the contents of palladium and platinum were determined. The Pd (palladium) content in every analysed sample was below the limit of quantification (< 10 ppb). The Pt (platinum) content in most analysed samples was also below the limit of quantification (< 10 ppb). The germanium (Ge) content was likewise below the limit of quantification (< 0.1 ppm) in the analysed samples.

Based on the conducted study, it can be concluded that coal mining waste is characterised by low contents of platinum group metals, at the level of several ppb, as well as germanium, and their recovery is economically unjustified. The cost of recovery technologies and separation operations exceeds the potential market value of the metal obtained from the processed material. For these reasons, the contents of platinum group metals and germanium in coal mining waste are not analysed in detail in this report.

In the following part of the report, the contents of the following elements were analysed:

- major components: SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, MnO, Cr_2O_3;
- REEs: Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu;
- selected CRM metals: Ba, Be, Bi, Co, Cu, Ga, Hf, Li, Nb, Ni, Ta, Sr, W, V;
- selected CRM metalloids: As, B.

The tables below (Tables 2-21) present descriptive statistics for the elemental contents in the coal mining waste samples, including minimum and maximum contents, quartiles, standard deviation, and sample size. The variability of selected elements in coal mining waste was analysed in detail according to the sampling location, i.e. six heaps in Poland, two heaps in Spain, and two boreholes in Greece (Tables 2-21 and Fig. 7-13). The data was presented in a box plot type graphs. Box plots show the distribution of selected elements in each analysed group. The line inside the box represents the median (Q2). The lower and upper edges of the box correspond to the first quartile (Q1, 25%) and the third quartile (Q3, 75%), respectively. The whiskers extend to the most extreme points lying within 1.5 × the interquartile range (IQR) of the box edges. Points beyond the whiskers indicate outliers.

Based on the presented box plots, it can be concluded that the investigated heaps show a certain degree of geochemical differentiation, more pronounced than that observed for the previously analysed and described variants. For many parameters, the interquartile ranges of the individual series overlap only partly or are clearly separated from one another, indicating that the material derived from the analysed heaps is not homogeneous in character. At the same time, for some series, the spread of results is relatively small, indicating fairly good internal homogeneity of certain sites, alongside distinct differences between the heaps themselves. The average REE contents in waste samples collected from heaps in Poland, Spain, and Greece are 215 ppm, 220 ppm, and 141 ppm, respectively.

<u>Coal mining waste samples collected from heaps in Poland</u>

With regard to the major components, substantial variation in TOT/C content can be observed. The highest values occur in series E1 and E2, and relatively high values are also found in series D, whereas the lowest contents were recorded in series F and especially in series G. Series A occupies an intermediate position. This means that the proportion of carbonaceous matter varies distinctly between the investigated heaps. Even stronger differentiation is visible for TOT/S. Series A stands out with the highest sulphur content by far, whereas E1, E2, D, and G are characterised by low values, and F occupies an intermediate position. This pattern indicates a very different material composition among the individual sites with respect to sulphur content and may reflect mineralogical differences, including the content of sulphides or secondary oxidation products.

Clear differences between the series can also be observed in the case of the major components expressed in oxide form. SiO_2 content is highest in series F and G, and relatively high also in A, whereas it is lower in E1, E2, and D. In turn, Al_2O_3 content reaches its highest values in series G, is also high in E1, E2, and D, and is clearly lower in F and especially in A. This indicates that the individual heaps differ not only in the degree of carbonisation of the material, but also in the proportion of aluminosilicate and silica phases. The highest Fe_2O_3 contents are observed in series F, and elevated values also occur in G, whereas lower values are found in E1, A, and D. This may indicate a greater presence of iron-bearing minerals.

Clear differences between the heaps are also observed when analysing MgO and CaO contents. The highest MgO content is shown by series F, with high values also in G, whereas series A stands out by having distinctly the lowest values. In the case of CaO content, the highest medians are recorded in series F, while A is characterised by the lowest values. The highest Na_2O content occurs in series F and G, whereas the remaining series have lower and more similar contents. K_2O content is highest in series E2 and G, moderate in E1, A, and D, and lowest in series F. P_2O_5 content is likewise highest in series D, whereas series A is characterised by the lowest content of this component. MnO content is clearly highest in series F and lowest in A, which further emphasises the geochemical differentiation of these two sites.

With respect to rare earth elements and associated elements, the differences between the series are very clearly visible. The contents of Y, La, Ce, and Nd are highest in series E1 and E2, relatively high also in D and G, and distinctly lower in F and A. An analogous pattern was obtained for the aggregate indicators SUM La_Ce_Nd and SUM REE. The highest REE contents (sum of 16 elements) occur in series E1 and E2, slightly lower values in D and G, and the lowest in series F and A. This means that, from the point of view of rare earth element concentration, the materials represented by series E1 and E2 appear the most promising, whereas series F and A are the least favourable in this respect.

In the group of other trace elements, strong differentiation between the sites is also evident. Series F is distinguished by the highest contents of As, Co, Li, MnO, Fe_2O_3, and CaO, as well as relatively high concentrations of some other components. Series A, in contrast, is characterised by the highest B content, while at the same time showing low concentrations of many other components, such as MgO, Na_2O, MnO, Li, Ni, and REEs. Series D stands out by a very high Sr content and elevated P_2O_5 content, whereas series G is characterised by relatively high values of Ga, Nd, Na_2O, SiO_2, Al_2O_3, and MgO, while at the same time having a low total carbon content.

It is also worth noting that series E1 and E2 are, in many respects, similar to each other, although not identical. Both are characterised by high TOT/C contents, relatively high REE sums, high Y, La, Ce, and Nd, and relatively low sulphur content. At the same time, series E2 shows higher values of K_2O, Cr_2O_3, Cu, Nb, and especially Ba than E1, whereas E1 has slightly higher Y and comparably high REE contents. This may indicate that the two sites represent a similar material type, but differ in the proportion of certain mineral fractions and trace admixtures.

When analysing the internal variability of the individual series, it can be noted that some series, especially A and partly F, show a greater spread of results for selected parameters, which may indicate greater heterogeneity of the material within the heap. In contrast, series D and G are in many cases more concentrated around the median, suggesting a greater averaging of sample composition. The presence of individual outliers, for example, for As, Ba, Cu, CaO, or TOT/S, indicates, however, that even within apparently homogeneous heaps there may be local zones with higher concentrations of specific components.

In summary, it can be concluded that the investigated hard coal waste heaps represent significantly different types of geochemical material. Series E1 and E2 are characterised by high total carbon content and the highest REE concentrations, making them the most promising from the perspective of rare earth elements. Series F is distinguished by high contents of Fe_2O_3, MgO, CaO, Na_2O, MnO, As, Co, and Li, but lower REE levels. Series A is strongly enriched in sulphur and boron, while being depleted in many other components. Series D is characterised by high Sr content and elevated P_2O_5 content, whereas series G shows relatively high contents of certain mineral components and selected trace metals, but low carbon content. The obtained results indicate considerable variability in the chemical composition of material collected from the selected Polish heaps, which should be taken into account when assessing the raw material, environmental, and technological potential of the investigated material.

Coal-mining wastes collected from spoil heaps in Spain

The value distributions for many components show limited overlap of the interquartile ranges, suggesting that the materials from the two spoil heaps are characterised by distinct geochemical profiles. At the same time, for some parameters, the variability within each series remains relatively low, indicating fairly good material homogeneity within the individual spoil heaps.

The most pronounced differences between the series concern the major components, expressed as oxides, and the content of the mineral fraction. The FSB/B samples are characterised by a markedly higher SiO_2 content, accompanied by clearly lower Al_2O_3 and TOT/C contents, indicating a more silica-rich character of the material and a lower proportion of carbonaceous matter. In contrast, the FSB/L samples show a significantly higher TOT/C content, as well as higher concentrations of Al_2O_3 and, partly, Fe_2O_3, which may suggest a greater contribution of organic matter and aluminosilicate and ferruginous mineral components. A particularly strong contrast between the series is observed for CaO and MgO, whose contents are significantly higher in the FSB/B series than in the FSB/L series. This may indicate a greater contribution of carbonate phases or other calcium- and magnesium-bearing minerals in the waste from the El Bierzo spoil heap.

For the remaining major components, differences between the two series are also evident. The FSB/L samples are richer in K_2O and TiO_2, whereas in the case of Na_2O the differences are smaller, although the median values are higher for the FSB/B series. The MnO content is higher in the FSB/B material, further confirming the geochemical distinctiveness of the two spoil heaps. For P_2O_5, the content ranges in the samples from both series partially overlap; therefore, the differences between the series can be considered moderate in this case.

The differentiation between the spoil heaps becomes even more pronounced with respect to trace elements and rare earth elements. For Sc, Y, La, Ce and Nd, both the median values and content ranges are consistently higher in the FSB/L samples than in the FSB/B samples. This indicates higher concentrations of REE and associated elements in the material from the Laciana spoil heap (FSB/L) compared with the material from El Bierzo (FSB/B). This is also confirmed by the SUM REE parameter, which reaches higher values in the FSB/L series, with relatively limited overlap of the ranges. From the perspective of rare earth element recovery potential, it can therefore be concluded that the material from the Laciana spoil heap (FSB/L) is more favourable than the material from the El Bierzo spoil heap (FSB/B).

Similar relationships are observed for several other trace elements. The FSB/L samples show higher contents of Ba, Co, Cu, Ga, Nb, Ni, Sr and, particularly, V, for which the differences between the series are very pronounced. The relatively higher concentrations of these components indicate that the material from the Laciana spoil heap is generally richer in trace elements associated with the mineral matter. In contrast, the FSB/B samples are distinguished by a higher Li content, which represents an important exception to the general trend of higher trace-element concentrations in the FSB/L series. In the case of As, the content ranges partially overlap, and a single clearly outlying value is also visible in the FSB/B series. For B, interpretation is limited due to the low variability and narrow content range; however, the data do not indicate any significant systematic differentiation between the series.

The degree of internal variability within the two spoil heaps is also noteworthy. For many parameters, the FSB/L series shows relatively narrow interquartile ranges, suggesting a more homogeneous material composition. In the FSB/B series, wider distributions or single outliers are observed for some indicators, which may reflect greater local compositional heterogeneity. Nevertheless, this does not change the overall picture, according to which the differences between the spoil heaps are greater than the variability within each spoil heap.

In summary, the investigated hard-coal wastes from the Laciana (FSB/L) and El Bierzo (FSB/B) spoil heaps show significant geochemical differentiation. The FSB/B material is characterised by higher contents of SiO_2, CaO, MgO, Na_2O, MnO and Li, whereas the FSB/L material is clearly enriched in TOT/C, Al_2O_3, K_2O, TiO_2, as well as in most of the analysed trace elements and REE, including Sc, Y, La, Ce and Nd, and in the total REE content. The obtained results therefore indicate that the two spoil heaps represent different types of waste material, and that, from the perspective of rare earth element and selected trace metal concentrations, the material from the Laciana spoil heap (FSB/L) is more prospective.

<u>Post-mining wastes collected from a spoil heap in Greece</u>

Based on the presented box plots, the chemical composition of the waste derived from the two Greek boreholes generally shows moderate variability. For some of the analysed components, more pronounced differences between the WPR-1 and WPR-2 series are visible, whereas for others, the value distributions are similar. In most cases, the interquartile ranges of the two series partially overlap, indicating that the investigated material is not highly lithochemically heterogeneous; however, local spatial differences between the boreholes are evident.

About the major components, the SiO_2 contents in both boreholes are very similar, with almost overlapping medians and interquartile ranges. This suggests the absence of significant differences between WPR-1 and WPR-2 in terms of the proportion of the silica component. Similarly, relatively minor differences are observed for TiO_2, K_2O and Al_2O_3, where the distributions of the results are comparable despite the occurrence of individual outliers. This indicates that these components show rather limited variability between the boreholes.

Differences between the WPR-1 and WPR-2 series are visible in the contents of CaO, Na_2O, Fe_2O_3, MgO and TOT/C. In the case of CaO, both the median and the upper range of values are higher in the WPR-2 samples, which may indicate a greater contribution of calcium-bearing phases or an admixture of material enriched in this component. Higher Na_2O contents are also observed in the WPR-2 series. In contrast, Fe_2O_3 and MgO show higher contents in the WPR-1 series, which may suggest local enrichment of the material in iron-bearing and magnesium-bearing components within this borehole. In the case of total carbon content (TOT/C), the median is higher in the WPR-2 series; however, the presence of outliers in both series indicates internal heterogeneity of the organic matter. The total sulphur content (TOT/S) in the WPR-1 and WPR-2 samples shows similar distributions, and the observed differences should be regarded as relatively minor.

Within the group of trace elements, some parameters indicate fairly distinct differences between the boreholes. This applies mainly to As, Co and, partly, Ni, V, Y, La, Ce and Nd, for which, in most cases, higher median values are recorded in the WPR-1 samples. This is particularly evident for As and Co, where the value distributions for the two boreholes are more clearly separated, and the WPR-1 samples generally show stronger enrichment. A similar, although less pronounced, trend is observed for Ni and V.

For Y, La, Ce and Nd, the distributions also indicate elevated contents in the WPR-1 series, suggesting that the material from this borehole may be slightly more favourable in terms of the concentration of selected rare earth elements. This is also confirmed by the compiled SUM REE parameter, which reaches higher median values in the WPR-1 samples than in the WPR-2 samples. At the same time, it should be emphasised that the ranges of values still partially overlap; therefore, the differences are moderate rather than extreme. This means that although the WPR-1 borehole shows a tendency towards greater enrichment in the analysed light REE, the material from both boreholes remains relatively comparable in terms of the concentration of this group of elements.

For some elements, such as B, Sr, Nb and Cu, the differences between the boreholes are weaker and less unequivocal. The box plots indicate substantial overlap of the value ranges, suggesting that, in these cases, variability is rather local and dispersed, and not systematically related to the borehole location. Similarly, for Cr_2O_3, the distributions of both series are quite similar, although WPR-1 shows a slightly higher median. It is also worth noting that outliers occur in many cases, indicating point-scale heterogeneity of the material.

In summary, there is noticeable but generally moderate variability in chemical composition between the WPR-1 and WPR-2 boreholes. For some major components, such as SiO_2, Al_2O_3, TiO_2 and K_2O, the differences are minor, indicating a relatively similar mineral character of the material in both locations. More pronounced differences are observed for CaO, MgO, Fe_2O_3 and some trace elements and REE. In particular, the samples from borehole WPR-1 show a tendency towards higher contents of Y, La, Ce, Nd and total REE, whereas the WPR-2 series is distinguished by higher contents of CaO, Na_2O and, partly, TOT/C. The obtained results therefore indicate that the material from the two boreholes is not geochemically identical; however, the differences are not large enough to suggest a completely distinct character of the investigated wastes. It is most appropriate to define them as materials with a similar overall chemical profile, but with local differences in the concentrations of individual components. Although the Greek material generally shows lower REE concentrations compared with the Polish and Spanish spoil heap materials, locally elevated Ni contents were observed, especially in the WPR-2 series. The mean Ni content in this series reached 903 ppm, with values ranging from 475 to 1361 ppm. This indicates that the raw material potential of the Greek spoil heap should not be considered only in relation to REEs.

Table 2. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from Coal waste heap A - Poland

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	18	18	18	18	18	18	18	18	18	18	18	18	18
Mean content	11.40	2.47	49.60	17.00	4.76	0.91	0.58	0.26	2.39	0.67	0.04	0.02	0.011
Standard deviation	2.05	0.74	3.70	1.38	0.79	0.22	0.71	0.04	0.23	0.05	0.01	0.00	0.001
Minimum content	8.72	1.28	43.50	13.30	3.38	0.76	0.25	0.17	1.95	0.52	0.03	0.02	0.009
Q1 (25%)	9.26	1.84	47.10	17.10	4.31	0.80	0.31	0.25	2.31	0.66	0.04	0.02	0.010
Q2 (50%)	11.40	2.47	50.00	17.30	4.63	0.85	0.33	0.27	2.40	0.69	0.04	0.02	0.011
Q3 (75%)	12.70	2.79	53.20	17.80	5.27	0.87	0.41	0.28	2.58	0.70	0.04	0.02	0.012
Maximum content	14.30	4.00	54.10	18.10	6.28	1.52	2.58	0.34	2.69	0.70	0.05	0.03	0.013

Table 3. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from Coal waste heap A - Poland

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Mean content	14.0	19.1	33.2	64.8	28.0	188	4.98	32.6	488	9.61	41.5	22.1	20	12.6	29.3	72.9	112
Standard deviation	1.2	1.5	2.8	5.5	2.4	15.4	1.21	2.62	52.1	0.96	6.14	1.97	1.89	1.2	4.84	6.05	8.74
Minimum content	11.0	15.9	26.6	51.5	22.2	150	2.9	29	399	7.9	29.9	16.8	16.8	9.6	21	63.7	88
Q1 (25%)	14.0	18.3	32.5	63.5	27.6	184	4.12	31	448	9.12	37.4	22.3	18.8	12.5	26.2	68.5	110
Q2 (50%)	14.0	19.5	33.4	65.5	28.5	190	4.95	31.5	494	9.55	41.2	22.6	19.9	12.9	29.5	71.2	113
Q3 (75%)	15.0	19.9	35.0	68.7	29.6	200	5.88	35.5	525	9.97	45.6	23	20.7	13.4	33.8	79.5	118
Maximum content	15.0	21.1	37.1	71.2	30.9	205	7.1	37	603	11.5	50.3	23.5	23.2	13.8	36	81.5	121

Table 4. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from Coal waste heap D - Poland

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	9	9	9	9	9	9	9	9	9	9	9	9	9
Mean content	14.50	0.23	46.20	18.80	4.35	1.27	0.71	0.31	2.47	0.79	0.13	0.05	0.013
Standard deviation	1.46	0.03	1.61	0.42	0.60	0.08	0.12	0.04	0.08	0.02	0.02	0.01	0.001
Minimum content	12.20	0.20	44.10	18.10	3.50	1.15	0.60	0.26	2.35	0.77	0.12	0.04	0.012
Q1 (25%)	13.40	0.21	44.80	18.50	4.06	1.22	0.63	0.29	2.40	0.78	0.12	0.04	0.013
Q2 (50%)	14.70	0.22	46.70	18.80	4.21	1.24	0.67	0.30	2.48	0.79	0.13	0.05	0.013
Q3 (75%)	15.70	0.23	47.00	19.20	4.51	1.33	0.82	0.31	2.53	0.80	0.14	0.05	0.014
Maximum content	16.20	0.28	49.20	19.30	5.68	1.41	0.92	0.37	2.56	0.83	0.17	0.08	0.014

Table 5. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from Coal waste heap D - Poland

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Mean content	16.0	25.2	37.3	73.8	32.7	220.0	3.7	7	513	12.2	36.6	24.4	17.1	13.2	37	157.0	121
Standard deviation	0.7	0.6	0.7	1.7	0.7	4.2	0.4	1	17	0.4	2.7	0.8	0.8	0.4	4	10.0	4
Minimum content	15.0	24.0	36.3	71.6	31.6	214.0	2.9	6	486	11.7	33.4	23.1	16.0	12.6	31	143.0	114
Q1 (25%)	16.0	25.0	36.6	71.9	32.2	215.0	3.5	6	503	11.9	35.4	24.1	16.4	12.9	35	154.0	118
Q2 (50%)	16.0	25.4	37.4	74.1	32.7	221.0	3.6	7	510	12.2	35.7	24.6	17.1	13.0	37	156.0	121
Q3 (75%)	16.0	25.6	37.6	74.9	33.3	222.0	4.0	7	525	12.4	37.4	25.0	17.5	13.5	39	160.0	123
Maximum content	17.0	26.0	38.3	76.2	33.7	226.0	4.1	7	535	13.1	42.5	25.3	18.4	13.9	44	173.0	127

Table 6. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from Coal waste heap E1 - Poland

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	18	18	18	18	18	18	18	18	18	18	18	18	18
Mean content	16.50	0.24	45.90	18.70	4.29	1.35	0.59	0.36	2.85	0.78	0.09	0.06	0.014
Standard deviation	3.93	0.09	3.43	0.88	0.57	0.12	0.13	0.05	0.27	0.03	0.01	0.01	0.001
Minimum content	6.88	0.11	42.30	17.30	3.39	1.13	0.40	0.28	2.48	0.71	0.08	0.04	0.012
Q1 (25%)	15.30	0.19	43.70	18.10	3.96	1.29	0.50	0.32	2.69	0.76	0.08	0.05	0.013
Q2 (50%)	17.40	0.23	44.80	18.60	4.15	1.33	0.57	0.34	2.79	0.78	0.09	0.06	0.014
Q3 (75%)	19.50	0.27	46.60	19.20	4.79	1.42	0.63	0.40	2.97	0.80	0.10	0.06	0.015
Maximum content	21.20	0.52	54.40	20.20	5.19	1.56	0.83	0.45	3.43	0.84	0.12	0.07	0.016

Table 7. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from Coal waste heap E1 - Poland

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Mean content	16.9	31.6	37.2	75.9	35.7	238.0	4.2	3	484	13.6	54.9	24.0	23.6	12.1	48	118.0	131
Standard deviation	0.7	1.8	1.6	3.4	1.7	10.6	1.6	0	24	0.5	9.0	0.9	1.8	0.9	5	6.7	7
Minimum content	16.0	28.4	34.9	71.9	33.5	225.0	2.7	2	445	12.7	36.0	22.2	19.4	10.7	38	108.0	121
Q1 (25%)	16.2	30.6	36.0	73.3	34.4	230.0	3.2	2	470	13.4	52.6	23.6	23.1	11.4	45	113.0	125
Q2 (50%)	17.0	31.4	36.8	74.8	35.5	235.0	3.5	3	484	13.6	55.9	24.1	23.4	12.0	49	118.0	130
Q3 (75%)	17.0	33.0	38.2	78.1	36.5	246.0	4.1	3	493	14.0	61.3	24.7	25.0	12.5	52	122.0	134
Maximum content	18.0	35.4	41.1	83.2	39.3	261.0	8.0	3	528	14.5	68.8	25.4	26.6	14.2	59	135.0	149

Table 8. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from Coal waste heap E2 - Poland

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	16	16	16	16	16	16	16	16	16	16	16	16	16
Mean content	15.20	0.28	46.20	18.90	4.92	1.40	0.79	0.37	2.90	0.78	0.11	0.06	0.015
Standard deviation	2.75	0.07	2.48	0.80	0.53	0.13	0.17	0.03	0.20	0.03	0.01	0.01	0.001
Minimum content	11.10	0.15	42.90	17.60	4.04	1.18	0.56	0.30	2.70	0.75	0.09	0.05	0.013
Q1 (25%)	12.50	0.21	44.30	18.30	4.57	1.33	0.69	0.36	2.75	0.76	0.10	0.06	0.014
Q2 (50%)	16.60	0.29	45.20	18.80	4.83	1.43	0.73	0.38	2.78	0.78	0.11	0.06	0.015
Q3 (75%)	17.40	0.32	49.00	19.40	5.24	1.47	0.84	0.39	3.08	0.81	0.12	0.07	0.016
Maximum content	18.20	0.38	49.80	20.20	5.80	1.61	1.14	0.41	3.20	0.82	0.14	0.08	0.017

Table 9. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from Coal waste heap E2 - Poland

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Mean content	17.0	30.4	37.5	75.6	34.9	234.0	5.1	3	701	14.7	47.8	24.8	23.5	13.1	46	142.0	134
Standard deviation	0.9	1.1	2.6	4.6	2.1	12.4	1.5	0	269	0.9	4.6	1.3	2.4	0.9	3	24.4	8
Minimum content	16.0	28.7	34.9	70.6	32.3	220.0	2.9	2	494	12.8	40.5	22.9	18.3	11.5	41	108.0	122
Q1 (25%)	16.0	29.3	35.2	71.8	33.3	224.0	3.6	3	534	14.4	44.5	23.8	22.3	12.6	43	122.0	126
Q2 (50%)	17.0	30.3	37.0	73.8	34.2	230.0	5.3	3	634	14.9	48.9	24.6	24.1	13.4	45	141.0	135
Q3 (75%)	18.0	31.1	39.1	78.3	36.5	244.0	6.4	3	723	15.4	52.1	25.7	25.3	13.8	48	166.0	139
Maximum content	18.0	32.2	42.0	83.4	38.3	255.0	7.0	3	1380	15.9	53.3	27.1	26.7	14.4	51	172.0	147

Table 10. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from Coal waste heap F - Poland

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	14	14	14	14	14	14	14	14	14	14	14	14	14
Mean content	8.65	0.44	52.10	16.00	6.46	1.89	0.91	0.81	2.29	0.80	0.12	0.12	0.015
Standard deviation	1.48	0.23	1.96	1.27	0.33	0.08	0.42	0.17	0.13	0.05	0.02	0.03	0.002
Minimum content	5.82	0.16	49.60	14.30	6.14	1.75	0.56	0.57	2.09	0.72	0.10	0.10	0.012
Q1 (25%)	7.95	0.22	50.40	14.90	6.23	1.85	0.58	0.64	2.23	0.76	0.11	0.10	0.014
Q2 (50%)	8.67	0.38	52.60	16.30	6.30	1.89	0.72	0.86	2.30	0.82	0.12	0.12	0.016
Q3 (75%)	9.43	0.62	53.10	16.90	6.80	1.94	1.23	0.95	2.35	0.84	0.14	0.15	0.017
Maximum content	10.90	0.82	55.70	18.00	7.05	2.03	1.68	1.04	2.53	0.86	0.14	0.17	0.017

Table 11. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from Coal waste heap F - Poland

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Mean content	15.9	25.5	30.5	62.3	29.2	196.0	11.8	19	452	17.7	42.7	20.6	40.1	12.4	47	102.0	130
Standard deviation	1.2	2.1	2.4	5.0	2.5	15.7	7.6	2	26	1.3	29.7	1.7	2.6	0.9	5	10.8	9
Minimum content	14.0	21.8	26.2	53.1	24.8	168.0	4.6	16	397	15.5	28.6	17.9	36.7	11.0	37	86.9	115
Q1 (25%)	15.0	24.2	29.2	60.0	28.0	187.0	5.0	18	440	16.8	32.1	19.4	37.4	11.9	43	94.3	122
Q2 (50%)	16.0	25.4	30.4	61.6	28.6	194.0	12.6	19	458	17.5	33.1	21.1	40.5	12.4	48	99.0	132
Q3 (75%)	17.0	27.4	32.5	66.8	31.6	210.0	14.9	21	471	18.9	36.3	21.9	42.2	12.8	51	112.0	139
Maximum content	17.0	28.0	33.8	68.6	32.4	215.0	31.0	23	484	19.8	142.0	22.8	44.1	13.9	53	117.0	141

Table 12. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from Coal waste heap G - Poland

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	12	12	12	12	12	12	12	12	12	12	12	12	12
Mean content	6.18	0.10	51.40	20.50	5.28	1.78	0.82	0.74	2.77	0.75	0.12	0.07	0.011
Standard deviation	1.03	0.05	1.03	0.68	0.91	0.13	0.14	0.08	0.07	0.02	0.02	0.02	0.001
Minimum content	4.84	0.05	49.10	19.50	4.63	1.64	0.62	0.60	2.63	0.71	0.10	0.05	0.010
Q1 (25%)	5.25	0.07	50.70	20.10	4.69	1.68	0.74	0.69	2.72	0.73	0.11	0.06	0.011
Q2 (50%)	5.98	0.09	51.70	20.40	4.79	1.78	0.80	0.74	2.77	0.75	0.12	0.07	0.011
Q3 (75%)	7.03	0.11	52.20	20.90	5.61	1.81	0.90	0.80	2.83	0.76	0.12	0.08	0.011
Maximum content	7.90	0.22	52.80	21.70	7.48	2.10	1.13	0.84	2.87	0.78	0.18	0.13	0.012

Table 13. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from Coal waste heap G - Poland

Parameter		Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
		ppm																
Number of samples		12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Mean content		14.1	26.7	35.1	71.7	33.0	216.0	3.5	9	555	11.9	28.8	28.3	34.8	13.9	31	105.0	98
Standard deviation		0.5	1.9	1.4	2.8	1.2	5.2	0.3	1	64	0.3	3.7	1.2	1.4	2.1	3	4.8	5
Minimum content		13.0	25.3	33.0	67.9	31.7	209.0	3.0	7	456	11.0	24.3	26.6	32.7	10.7	27	96.9	89
Q1 (25%)		14.0	25.4	34.3	70.3	32.5	213.0	3.4	8	510	11.8	25.0	27.3	33.9	11.8	29	102.0	94
Q2 (50%)		14.0	26.1	34.8	71.0	32.7	216.0	3.6	9	564	11.9	29.3	28.1	34.2	14.8	32	105.0	98
Q3 (75%)		14.0	26.9	35.5	71.8	33.0	218.0	3.7	10	598	12.1	32.0	29.1	35.8	15.2	33	109.0	100
Maximum content		15.0	32.1	37.7	77.3	35.7	226.0	3.9	10	648	12.3	33.7	30.2	37.7	16.2	36	111.0	107

Table 14. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from the Laciana spoil heap (FSB/L series samples) - Spain

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	10	10	10	10	10	10	10	10	10	10	10	10	10
Mean content	15.67	0.33	47.49	18.27	5.61	1.13	0.42	0.61	3.30	0.73	0.14	0.06	0.014
Standard deviation	5.55	0.51	4.11	1.31	1.12	0.07	0.11	0.08	0.18	0.05	0.02	0.01	0.001
Minimum content	8.75	0.11	40.61	15.64	4.10	1.01	0.30	0.47	2.99	0.62	0.12	0.04	0.012
Q1 (25%)	11.63	0.14	45.95	17.67	5.06	1.09	0.36	0.58	3.19	0.69	0.12	0.06	0.013
Q2 (50%)	15.81	0.18	47.61	18.81	5.43	1.11	0.38	0.62	3.34	0.75	0.13	0.06	0.014
Q3 (75%)	16.83	0.23	51.04	19.12	5.73	1.16	0.48	0.67	3.40	0.76	0.14	0.07	0.014
Maximum content	24.81	1.79	52.32	19.41	8.26	1.23	0.66	0.74	3.55	0.79	0.18	0.08	0.016

Table 15. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from the Laciana spoil heap (FSB/L series samples) - Spain

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Mean content	15.4	26.3	40.5	80.0	34.7	233.6	17.1	1	751	16.8	43.6	24.6	24.1	14.0	43	117.1	144
Standard deviation	1.1	1.7	2.9	5.7	2.5	15.9	3.3	0	38	1.7	4.1	1.8	2.9	0.9	6	6.8	11
Minimum content	13.0	23.2	35.5	70.3	30.9	209.0	11.2	1	665	13.6	33.7	20.7	18.5	12.1	35	100.6	118
Q1 (25%)	15.3	25.6	38.6	76.1	32.8	221.8	14.7	1	737	16.2	41.9	24.2	22.9	13.4	40	116.1	142
Q2 (50%)	16.0	26.7	41.8	82.2	35.3	239.5	18.1	1	763	16.8	44.7	25.3	24.4	14.4	44	118.4	147
Q3 (75%)	16.0	27.4	42.2	83.4	36.2	243.3	18.7	1	774	17.5	46.2	25.4	25.4	14.6	45	120.9	151
Maximum content	16.0	29.1	44.0	87.3	38.1	255.0	22.0	1	794	19.3	48.0	26.4	29.1	15.0	57	125.3	157

Table 16. Descriptive statistics of the contents of major components in hard-coal waste samples – samples collected from the El Bierzo spoil heap (FSB/B series samples) - Spain

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	10	10	10	10	10	10	10	10	10	10	10	10	10
Mean content	3.62	0.22	64.25	14.47	5.31	1.31	1.40	0.68	2.86	0.67	0.13	0.10	0.010
Standard deviation	0.80	0.09	2.02	0.87	0.32	0.09	0.21	0.02	0.17	0.04	0.01	0.01	0.001
Minimum content	2.80	0.14	60.91	13.14	4.78	1.20	1.09	0.65	2.59	0.60	0.12	0.08	0.008
Q1 (25%)	3.24	0.16	62.91	13.84	5.09	1.25	1.25	0.66	2.76	0.63	0.13	0.09	0.009
Q2 (50%)	3.43	0.21	64.41	14.47	5.33	1.28	1.48	0.68	2.85	0.68	0.13	0.10	0.009
Q3 (75%)	3.82	0.25	65.61	15.20	5.48	1.36	1.53	0.69	3.00	0.71	0.14	0.10	0.010
Maximum content	5.66	0.45	67.37	15.77	5.87	1.47	1.73	0.72	3.13	0.72	0.14	0.11	0.012

Table 17. Descriptive statistics of REE and other critical elements in hard-coal waste samples – samples collected from the El Bierzo spoil heap (FSB/B series samples) - Spain

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Mean content	12.2	24.7	35.4	70.5	31.0	207.4	18.4	2	539	15.6	31.6	18.2	42.9	9.8	38	107.6	115
Standard deviation	0.9	2.0	2.7	5.4	2.2	15.6	9.2	0	34	1.5	2.0	1.5	2.1	0.8	3	9.7	8
Minimum content	11.0	21.5	31.0	61.6	27.2	182.0	12.4	1	484	12.7	29.2	15.8	39.2	8.5	35	89.7	103
Q1 (25%)	12.0	23.0	33.4	66.4	29.5	195.0	14.1	2	527	15.1	30.0	17.2	41.8	9.3	36	104.3	112
Q2 (50%)	12.0	24.8	35.7	70.7	31.1	207.5	14.9	2	536	15.6	31.1	17.9	42.7	9.9	38	107.6	115
Q3 (75%)	12.8	26.0	37.3	74.7	32.5	217.5	19.1	2	563	16.1	33.1	19.3	44.7	10.2	40	114.6	119
Maximum content	14.0	27.4	40.1	79.5	34.6	233.0	43.3	2	592	18.8	35.1	20.4	45.6	11.0	43	118.9	127

Table 18. Descriptive statistics of the contents of major components in lignite waste samples – samples collected from the spoil heap (WPR-1 series samples) – LM-GR, Greece

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	25	25	25	25	25	25	25	25	25	25	25	25	25
Mean content	2.57	0.09	51.59	8.60	7.47	4.52	8.76	0.87	1.37	0.41	0.05	0.09	0.339
Standard deviation	1.88	0.04	10.57	1.57	1.49	1.40	6.93	0.46	0.32	0.08	0.01	0.02	0.094
Minimum content	0.51	0.04	30.11	5.64	4.14	2.96	1.63	0.30	0.81	0.26	0.04	0.05	0.173
Q1 (25%)	1.37	0.07	45.37	7.38	6.35	3.51	4.90	0.46	1.18	0.37	0.04	0.07	0.264
Q2 (50%)	1.96	0.08	51.58	8.89	7.45	4.25	6.03	0.76	1.40	0.41	0.05	0.09	0.348
Q3 (75%)	2.78	0.11	56.86	9.26	8.43	5.16	10.10	1.25	1.56	0.43	0.05	0.11	0.415
Maximum content	7.22	0.21	68.90	12.23	10.70	7.81	26.56	1.80	1.96	0.60	0.07	0.13	0.494

Table 19. Descriptive statistics of REE and other critical elements in lignite waste samples – samples collected from the spoil heap (WPR-1 series samples) – LM-GR, Greece

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	25	25	25	25	25	25	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25	25.0	25
Mean content	11.6	23.1	23.0	45.6	20.6	148.8	2.3	3	199	76.1	19.2	10.5	11.3	9.2	1123	71.5	68
Standard deviation	3.2	4.1	4.5	8.3	3.9	27.1	0.7	1	33	20.1	5.8	2.1	3.1	1.6	366	10.8	15
Minimum content	7.0	14.6	15.8	31.8	14.2	99.8	1.2	2	135	36.7	11.8	7.4	7.2	6.6	549	54.4	45
Q1 (25%)	10.0	19.8	19.2	38.4	17.2	126.1	1.6	2	179	63.0	15.3	9.0	9.1	8.2	855	63.7	59
Q2 (50%)	11.0	23.5	22.7	46.2	20.5	149.0	2.4	3	207	76.8	17.3	10.5	10.3	9.3	1112	69.6	64
Q3 (75%)	12.0	25.6	24.7	49.9	22.4	161.1	2.6	3	225	85.8	21.3	11.3	13.3	9.6	1260	76.6	72
Maximum content	22.0	30.8	32.0	59.8	28.2	205.6	4.3	4	255	123.7	38.4	15.6	19.1	12.6	2131	105.5	118

Table 20. Descriptive statistics of REE and other critical elements in lignite waste samples – samples collected from the spoil heap (próby seria WPR-2) – LM-GR, Greece

Parameter	TOT/C	TOT/S	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
	%												
Number of samples	25	25	25	25	25	25	25	25	25	25	25	25	25
Mean content	2.94	0.08	50.76	8.38	6.66	3.37	11.02	1.03	1.47	0.40	0.05	0.08	0.289
Standard deviation	1.56	0.03	9.76	1.20	1.13	0.62	6.30	0.36	0.35	0.06	0.01	0.02	0.093
Minimum content	0.69	0.04	29.32	5.37	4.31	2.16	2.22	0.45	0.65	0.29	0.04	0.06	0.137
Q1 (25%)	2.00	0.06	44.86	7.73	6.21	3.15	7.51	0.71	1.25	0.36	0.05	0.07	0.194
Q2 (50%)	2.54	0.08	52.10	8.65	6.49	3.23	8.34	0.99	1.48	0.39	0.05	0.08	0.322
Q3 (75%)	3.71	0.10	57.92	8.91	7.32	3.58	13.88	1.36	1.60	0.43	0.06	0.09	0.363
Maximum content	6.52	0.16	69.04	10.31	8.82	4.73	25.70	1.82	2.30	0.51	0.07	0.12	0.459

Table 21. Descriptive statistics of REE and other critical elements in lignite waste samples – samples collected from the spoil heap (próby seria WPR-2) – LM-GR, Greece

Parameter	Sc	Y	La	Ce	Nd	SUM REE	As	B	Ba	Co	Cu	Ga	Li	Nb	Ni	Sr	V
	ppm																
Number of samples	25	25	25	25	25	25	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25	25.0	25
Mean content	10.0	20.1	20.5	41.6	19.0	134.1	1.5	3	210	56.5	16.5	9.8	9.5	8.9	903	70.6	63
Standard deviation	2.0	2.7	3.5	6.7	3.1	20.8	0.4	1	87	11.0	3.8	1.5	2.1	1.3	231	10.9	10
Minimum content	7.0	13.6	13.7	27.2	12.6	91.3	0.9	2	122	32.8	11.7	6.1	6.4	6.0	475	52.8	48
Q1 (25%)	9.0	18.5	18.0	36.9	17.2	121.9	1.2	2	178	50.2	13.5	8.9	8.1	8.1	783	63.4	56
Q2 (50%)	10.0	20.2	20.1	41.2	18.6	132.3	1.4	3	203	55.5	16.2	10.0	9.0	8.8	845	67.0	63
Q3 (75%)	12.0	21.4	21.4	44.3	19.9	139.7	1.6	3	220	64.8	17.3	10.3	10.2	9.2	1089	77.4	68
Maximum content	14.0	25.5	27.4	53.9	24.9	174.8	2.3	4	602	80.0	25.2	12.5	13.9	11.2	1361	96.1	81

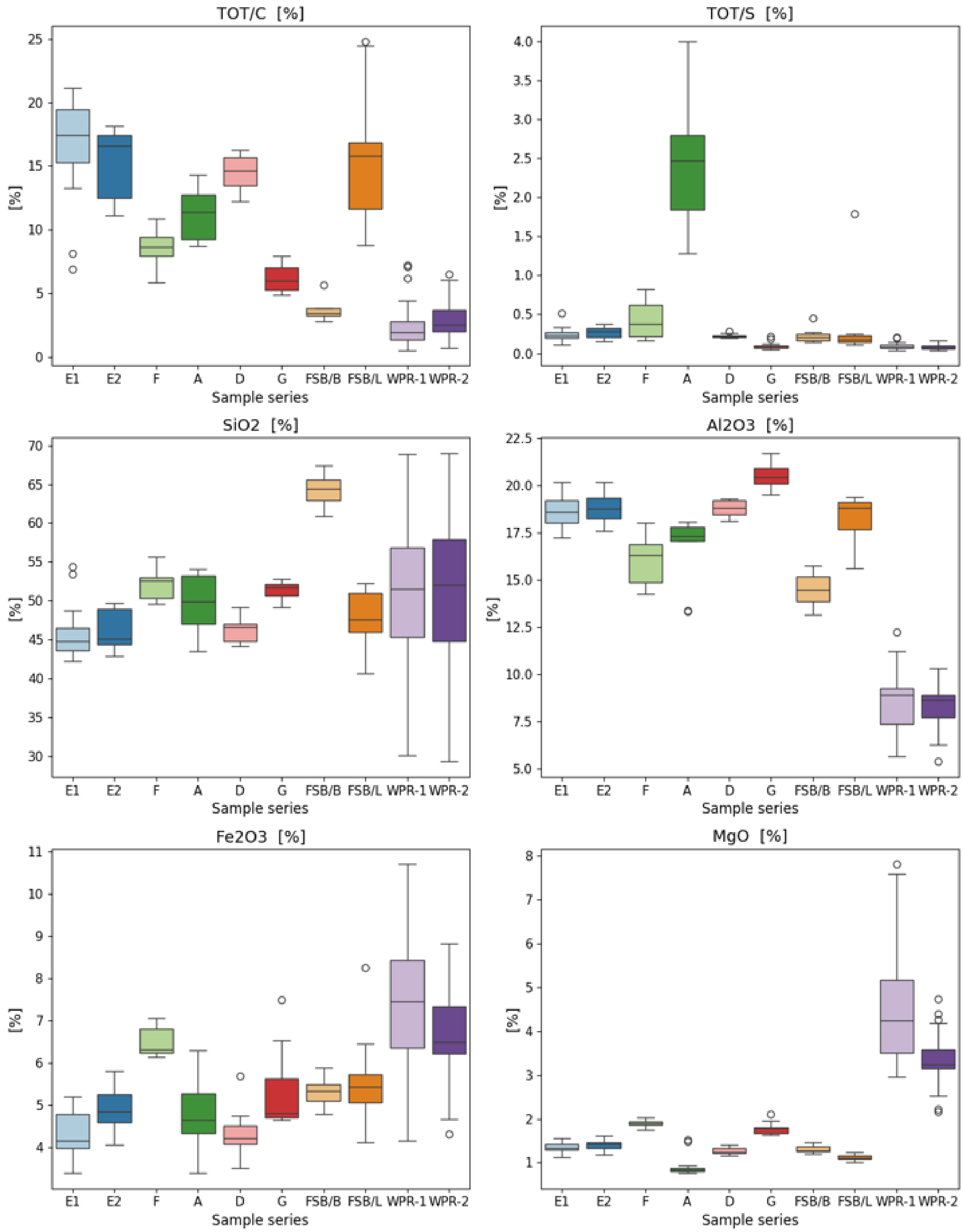

Figure 7. Variability in the contents of selected elements in post-coal wastes from Polish spoil heaps E1-G; Spanish spoil heaps: Laciana (FSB/L) and El Bierzo (FSB/B); and borehole 1 (WPR-1) and borehole 2 (WPR-2) from the LM-GR spoil heap in Greece

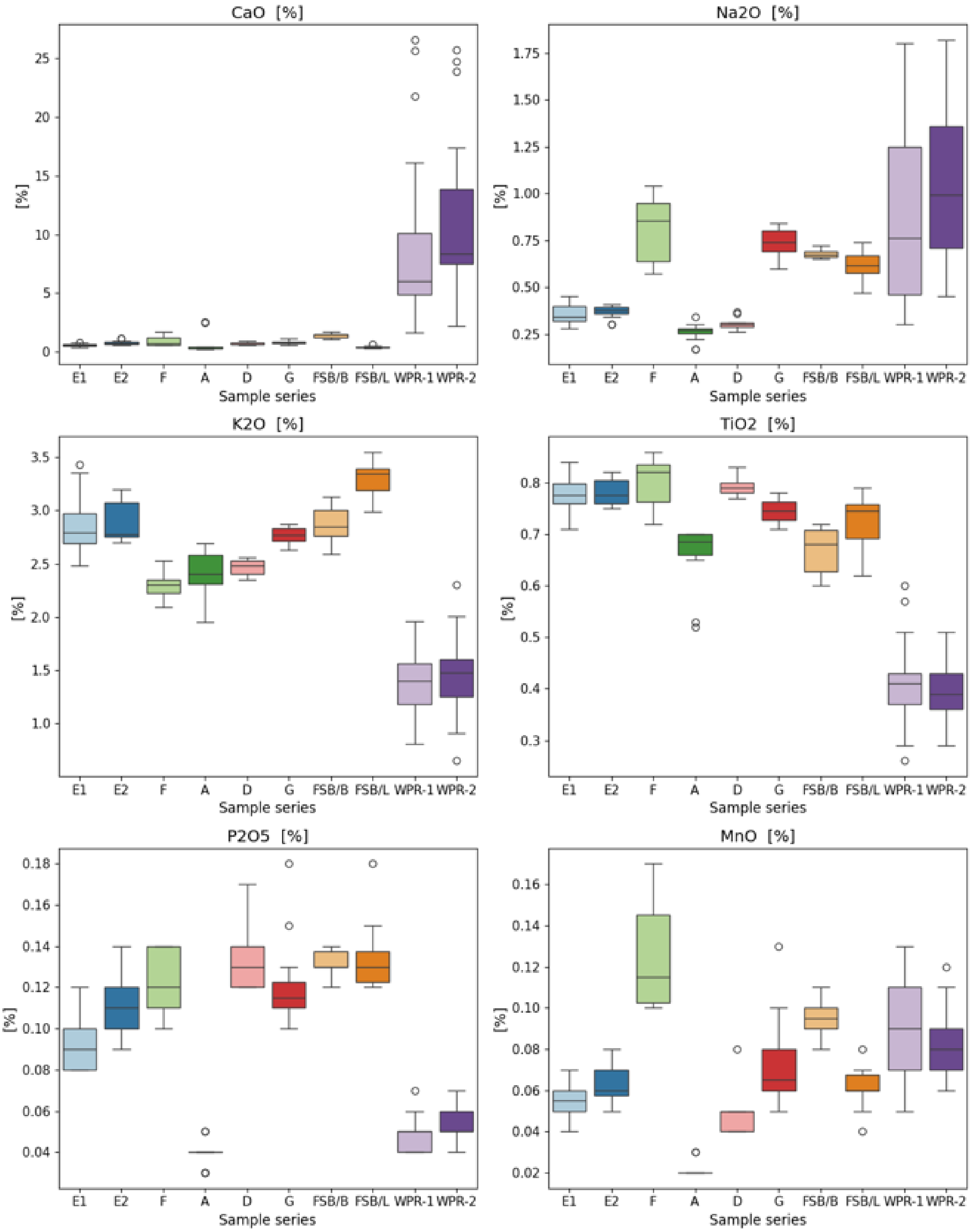

Figure 8. Variability in the contents of selected elements in post-coal wastes in samples collected from Polish spoil heaps E1-G; Spanish spoil heaps: Laciana (FSB/L) and El Bierzo (FSB/B); and borehole 1 (WPR-1) and borehole 2 (WPR-2) from the LM-GR spoil heap in Greece

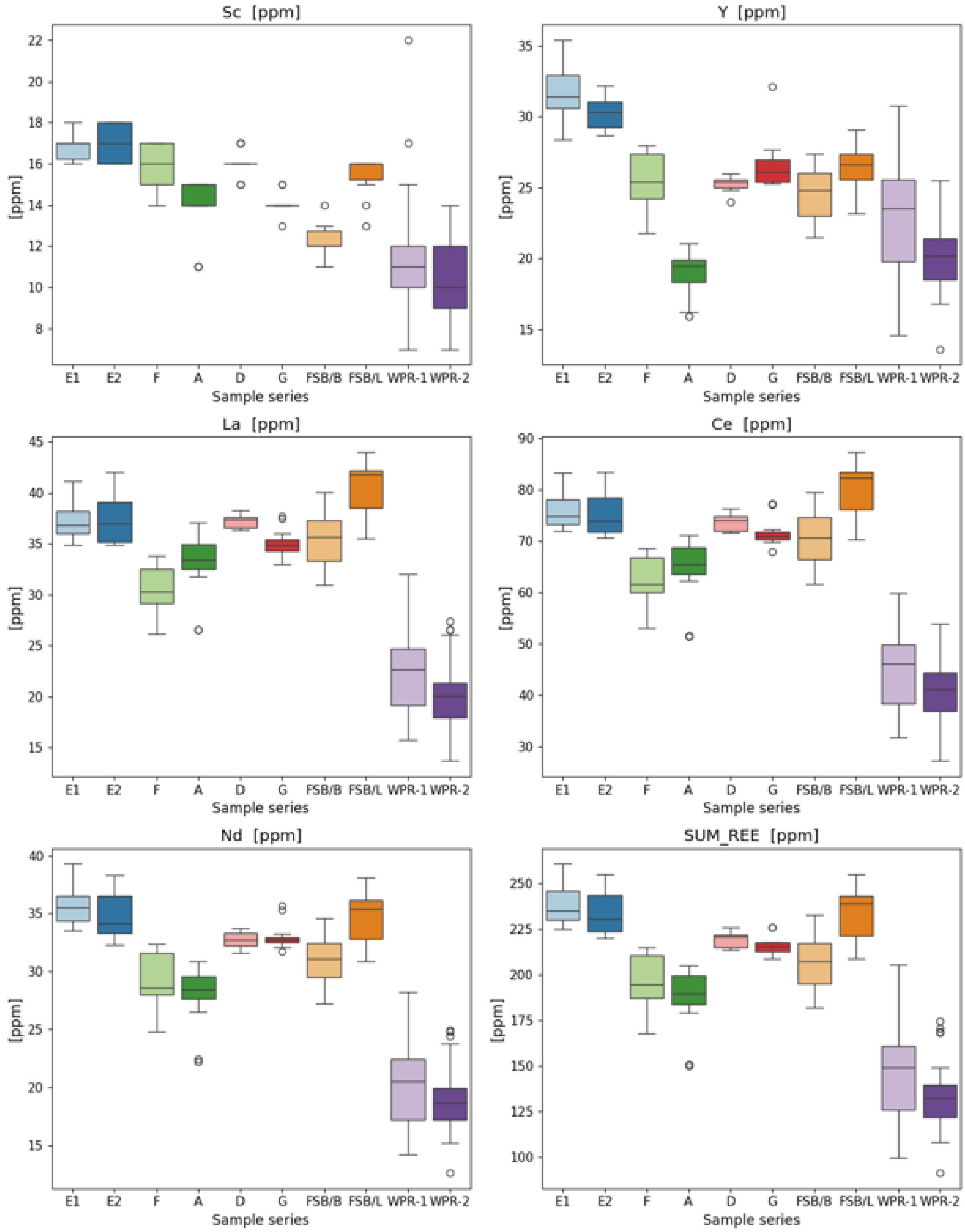

Figure 9. Variability in the contents of selected elements in post-coal wastes in samples collected from Polish spoil heaps E1-G; Spanish spoil heaps: Laciana (FSB/L) and El Bierzo (FSB/B); and borehole 1 (WPR-1) and borehole 2 (WPR-2) from the LM-GR spoil heap in Greece

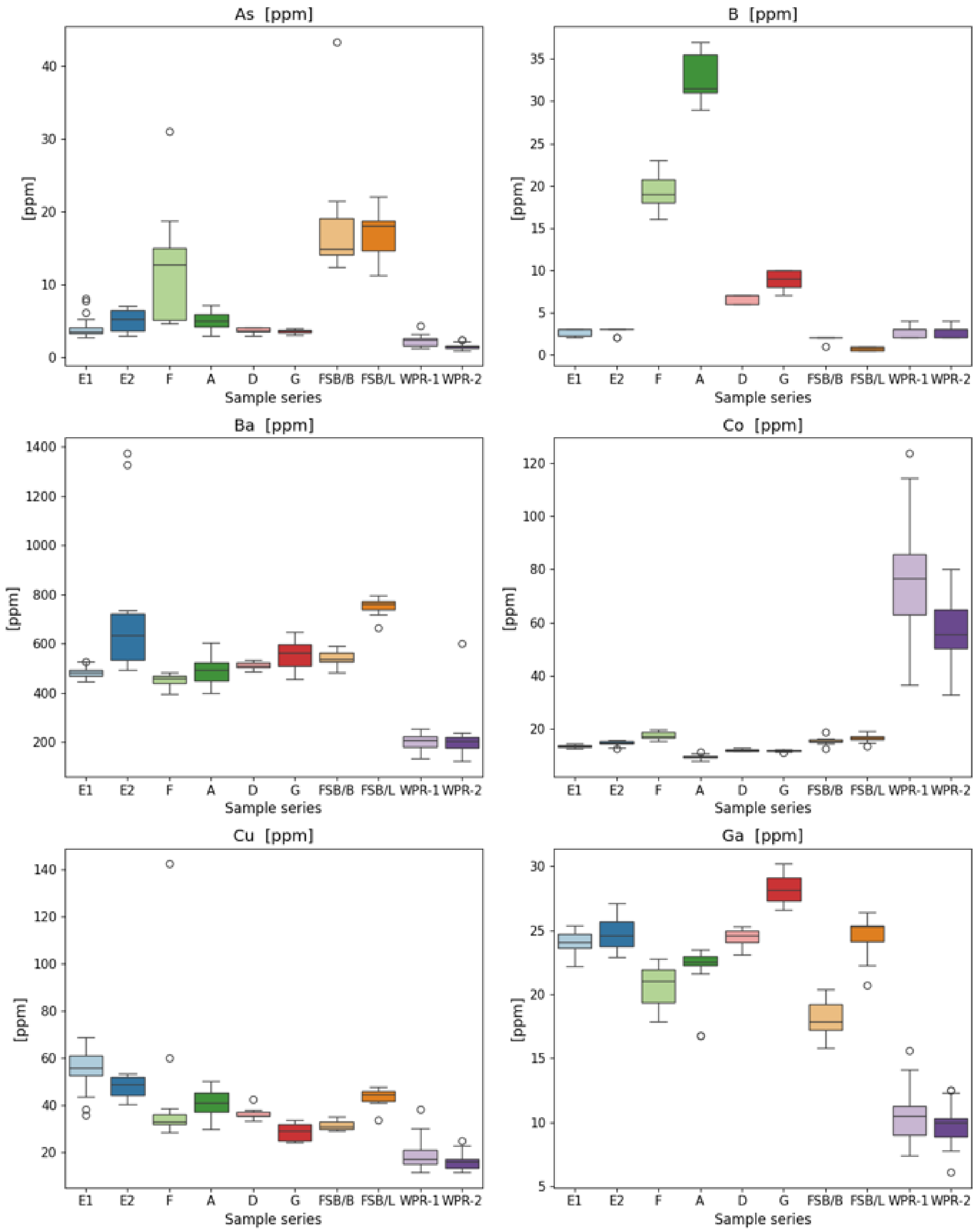

Figure 10. Variability in the contents of selected elements in post-coal wastes in samples collected from Polish spoil heaps E1-G; Spanish spoil heaps: Laciana (FSB/L) and El Bierzo (FSB/B); and borehole 1 (WPR-1) and borehole 2 (WPR-2) from the LM-GR spoil heap in Greece

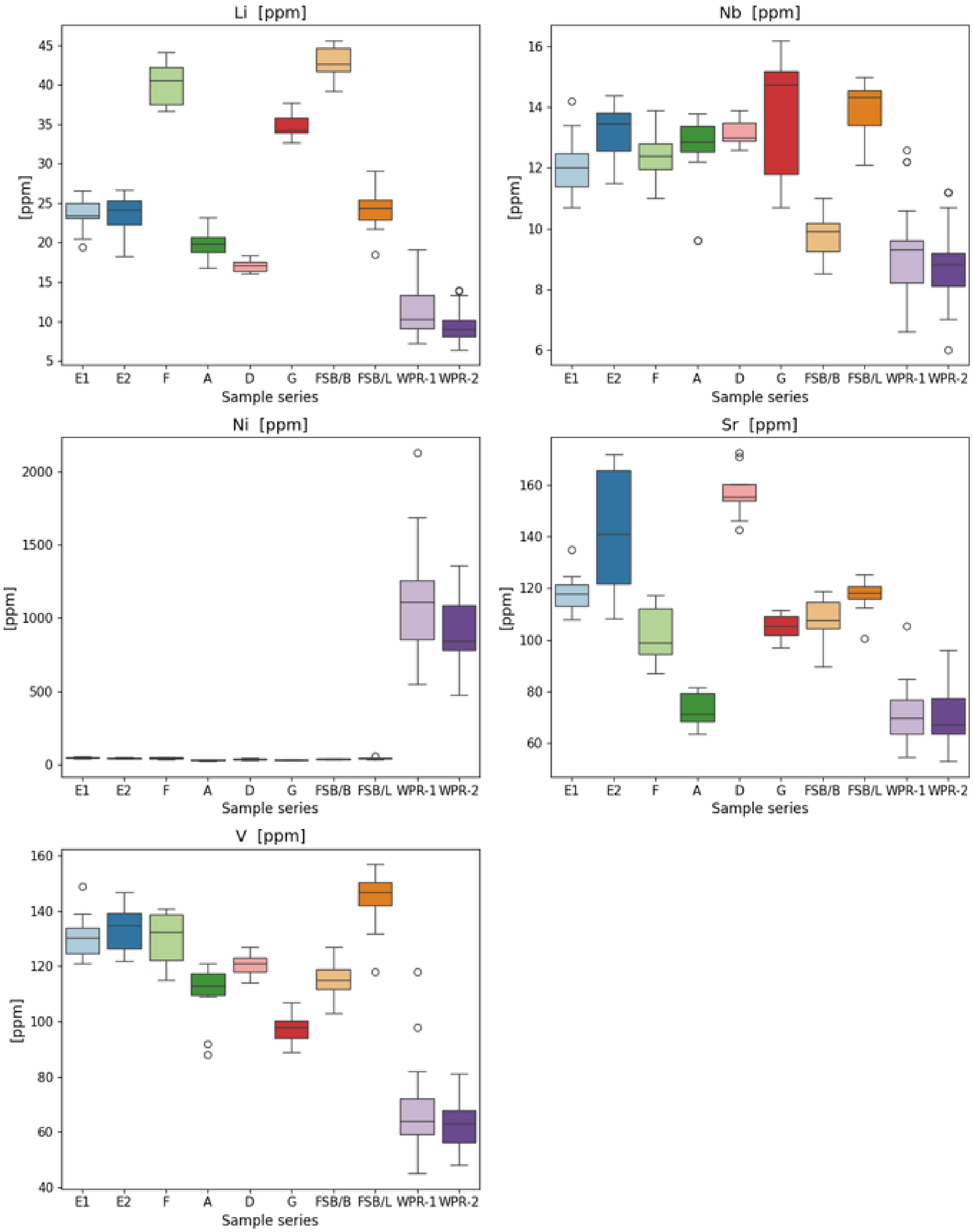

Figure 11. Variability in the contents of selected elements in post-coal wastes in samples collected from Polish spoil heaps E1-G; Spanish spoil heaps: Laciana (FSB/L) and El Bierzo (FSB/B); and borehole 1 (WPR-1) and borehole 2 (WPR-2) from the LM-GR spoil heap in Greece

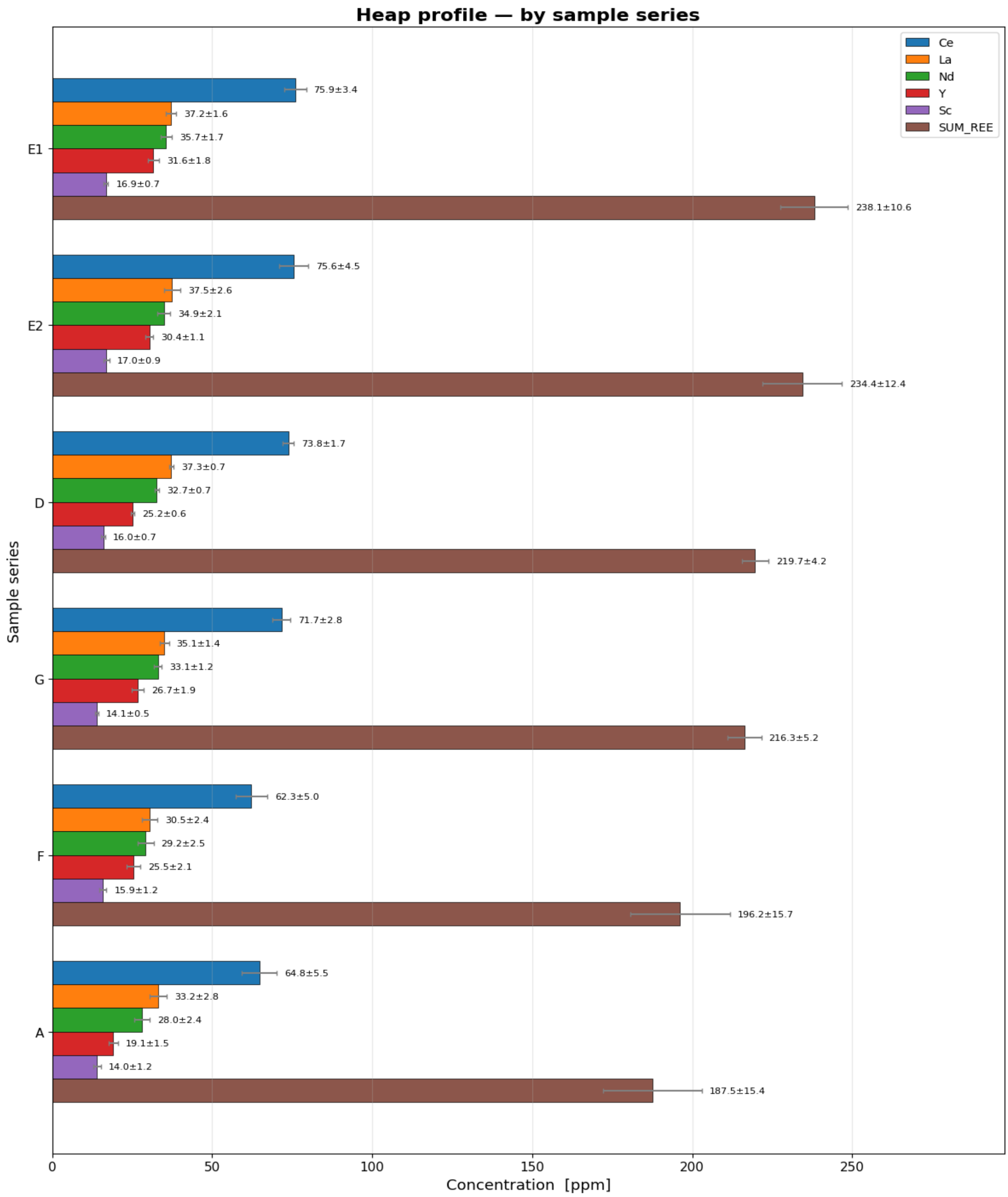

Figure 12. Mean contents of Ce, La, Nd, Y, Sc and total REE, calculated as the sum of 16 elements, in samples collected from Polish spoil heaps E1-G .

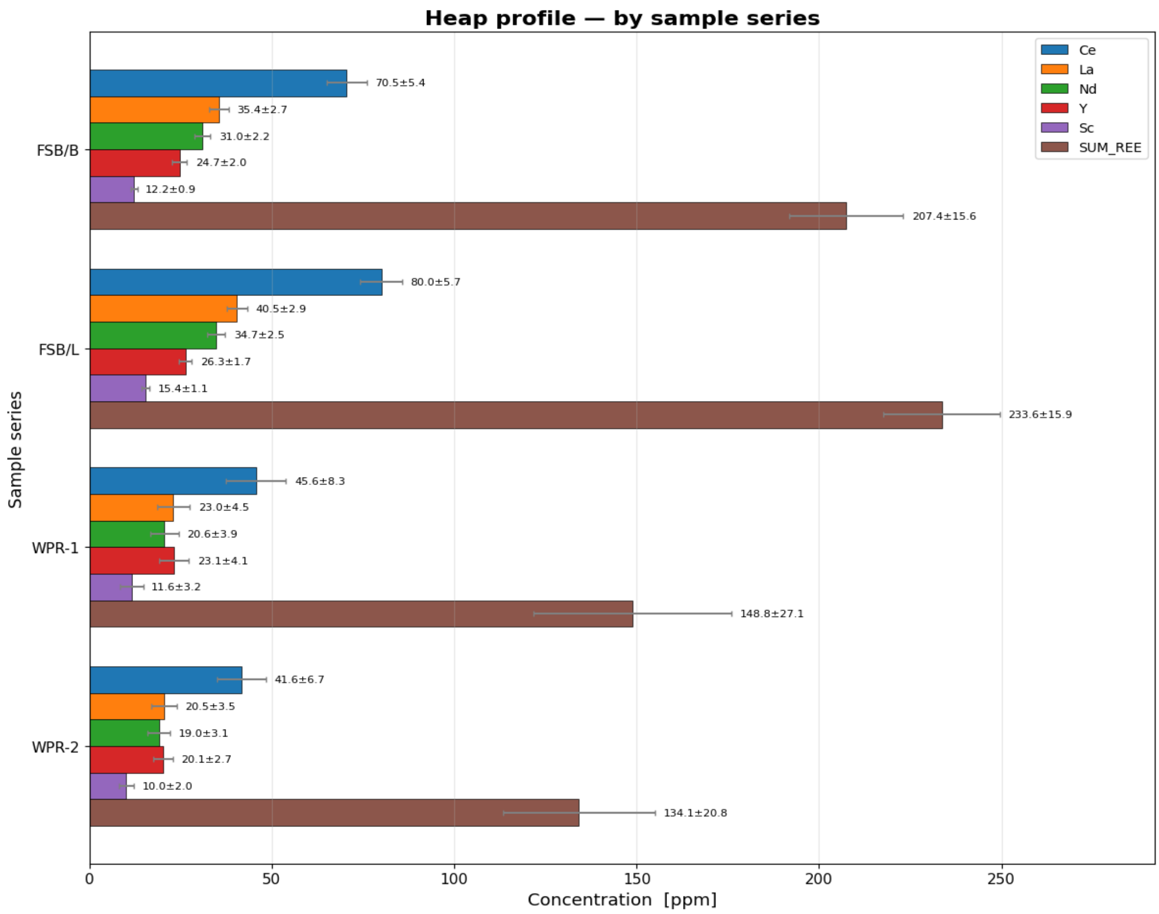

Figure 13. Mean contents of Ce, La, Nd, Y, Sc and total REE, calculated as the sum of 16 elements, in samples from the Spanish spoil heaps: Laciana (FSB/L) and El Bierzo (FSB/B), and from borehole 1 (WPR-1) and borehole 2 (WPR-2) from the LM-GR spoil heap in Greece.

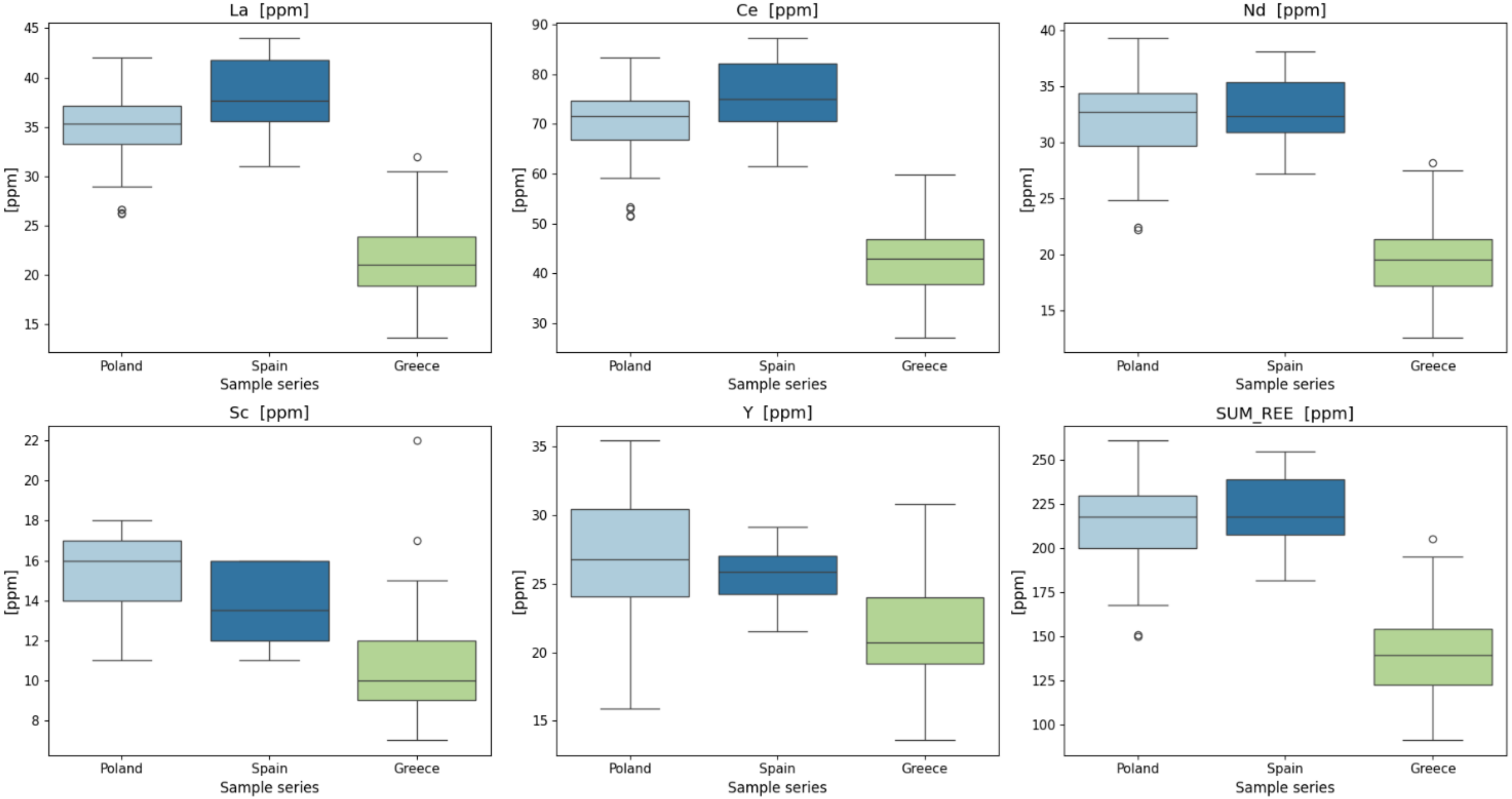

Figure 14. Mean contents of Ce, La, Nd, Y, Sc and total REE, calculated as the sum of 16 elements, in samples collected from Polish spoil heaps E1-G.

General comparison of rare earth element contents in spoil heaps from Poland, Spain and Greece

The presented chart (Fig. 14) shows clear differences between spoil heap materials from Poland, Spain and Greece in terms of the contents of selected elements. The most distinct differentiation concerns La, Ce, Nd and the total REE content, for which samples from Poland and Spain reach clearly higher values than samples from Greece. This indicates that the Greek wastes are generally characterised by lower concentrations of the analysed REEs, whereas the Polish and Spanish materials represent a higher and more comparable level.

In the case of lanthanum, the highest values were recorded in samples from Spain. The material from Poland reached slightly lower levels, while the Greek samples were clearly lower than both of the other groups. A very similar pattern is observed for cerium. Here, too, the highest concentrations occur in the Spanish material, slightly lower concentrations in the Polish material, and the lowest in the Greek material. For neodymium, the differences between Poland and Spain are less pronounced, as the value ranges partially overlap; however, Greece also remains the group with the lowest concentration in this case.

A slightly different relationship is observed for scandium. In this case, the highest values are recorded in the Polish samples, while the Spanish material reaches lower levels, although still higher than those observed in the Greek samples. It is worth noting that, for scandium, the Greek samples show individual outliers; however, this does not change the overall picture, according to which the Polish material is characterised by the highest content of this element. For yttrium, the differences between Poland and Spain are small. Poland shows slightly higher median values and a greater spread of results, whereas Spain presents a more concentrated distribution. Greece is also characterised by lower concentrations in this case.

From the perspective of assessing raw material potential, the most important chart is the one showing SUM REE. It indicates that the highest values of total rare earth element content occur in samples from Spain, while very similar, although slightly lower, values are observed in samples from Poland. The material from Greece reaches a clearly lower level. The differences between Poland and Spain are relatively small, whereas the distinct character of the Greek material is evident and is maintained for all analysed parameters.

The variability of results within individual groups is also noteworthy. In the Polish material, a greater spread is visible for some elements, which may indicate higher heterogeneity of the investigated spoil heaps. The Spanish material is more often concentrated around higher median values, suggesting a more uniform level of REE concentration. The Greek samples are generally poorer in the analysed elements, although individual higher values occur locally.

In summary, the comparison of spoil heap materials from the three countries indicates that the highest contents of La, Ce, Nd and SUM REE were found in samples from Spain, while very similar values were obtained for samples from Poland, and the lowest values were recorded for samples from Greece. At the same time, the Polish material is distinguished by the highest scandium concentration and slightly higher yttrium values. In light of these results, it can be concluded that, among the compared groups, wastes from Spain and Poland show higher REE concentrations, whereas the Greek material is characterised by a clearly lower level of these elements.

When interpreting the comparison between countries, however, it should be considered that the Polish sample set includes material from six spoil heaps, whereas the Spanish set is represented by only two spoil heaps. In addition, the number of individual samples from each spoil heap was significantly higher in the case of the Polish samples. This difference may affect the observed spread of results and the representativeness of both groups. The larger number of objects included in the Polish dataset probably better reflects the natural variability of chemical composition, whereas the results for Spain may be more strongly determined by the local properties of the investigated spoil heaps. This means that the differences identified between the Polish and Spanish materials should be interpreted with caution, as referring to the analysed sample sets rather than as an unequivocal characteristic of all spoil heaps in a given country.

4. Summary

The results presented in this report confirm that deposited coal and lignite mining wastes may represent a relevant secondary source of selected critical raw materials, including rare earth elements. This issue is of strategic importance for the European Union, as CRMs and REEs are essential for renewable energy technologies, electromobility, electronics, advanced materials, defence, aerospace, digital infrastructure and industrial decarbonisation technologies. At the same time, the EU remains highly dependent on imports of many of these raw materials, often from a limited number of non-European suppliers, which creates supply risks and strategic vulnerabilities. Therefore, the identification and assessment of domestic and European secondary sources of CRMs, including post-mining wastes deposited on spoil heaps, is an important element of strengthening raw material security and supporting circular economy strategies

The investigated materials were collected from deposited spoil heaps in Poland, Spain and Greece. The report focuses exclusively on already deposited mining wastes and does not include wastes from current mining or coal processing streams. This is an important aspect from the perspective of potential future recovery, because these materials are already accumulated in large volumes, are accessible at existing post-mining sites, and do not require the development of new primary mining operations. Consequently, such wastes should no longer be considered only as an environmental or land-management burden, but also as a potential secondary raw material resource.

A general comparison of the analysed materials indicates that the average total REE contents in samples collected from spoil heaps in Poland, Spain and Greece were approximately 215 ppm, 220 ppm and 141 ppm, respectively. The most distinct differences between the countries were observed for La, Ce, Nd and total REE content. Polish and Spanish materials reached higher and relatively comparable REE levels, while Greek wastes were characterized by lower concentrations of the analyzed REEs. This suggests that, among the investigated materials, the Polish and Spanish spoil heap wastes are more prospective in terms of REE content, although the recovery potential must also be assessed in relation to mineralogical occurrence, processing behaviour, extractability and economic feasibility. In the Greek lignite mining waste samples, particular attention should also be paid to nickel. Although the Greek material was generally characterized by lower REE contents than the Polish and Spanish spoil heap materials, the WPR-2 series showed markedly elevated Ni concentrations, with a mean content of 903 ppm and values reaching up to 1361 ppm. This indicates that the raw material potential of the Greek spoil heap should not be assessed only from the perspective of REEs. The elevated nickel content suggests that selected zones of the Greek waste deposit may be prospective with regard to specific CRM metals, even if their REE potential is comparatively lower.

Based on the obtained results, selected waste samples representing the most promising geochemical characteristics will be subjected to further technological studies aimed at assessing the practical recovery potential of CRMs and REEs. In the next stages of the Waste2CRM project, these materials will be processed using pre-concentration methods in order to enrich the fractions containing the target elements and reduce the mass of material directed to subsequent treatment. The pre-concentrated products will then be used in recovery tests based on hydrometallurgical methods. This approach will make it possible to verify not only the occurrence and concentration levels of CRMs and REEs in the investigated wastes, but also their technological availability and potential recoverability under process conditions. As a result, the project will provide a more complete assessment of the feasibility of transforming selected post-mining waste materials into secondary sources of critical raw material.