

Article

Geochemical Characterisation of Strategic Elements (Li, Co, Ni, Cu, Ga, Ge, and REEs) in Bottom Ash from the Thermal Power Plant (Afşin–Elbistan, Türkiye)

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Abstract

This study investigates the concentrations and geochemical behaviour of strategic elements—including Li, Co, Ni, Cu, Ga, Ge, rare earth elements (REEs), and yttrium (Y)—in bottom ash samples from the Afşin–Elbistan thermal power plant, Türkiye. Thirty bottom ash samples were analysed, revealing average Σ LREE and Σ HREE concentrations of 86.3 $\mu\text{g/g}$ and 3.3 $\mu\text{g/g}$, respectively, resulting in an L/H ratio of 24.9, indicating pronounced enrichment in light REEs. The total Σ REE + Y concentration (111 $\mu\text{g/g}$) is comparable to the background value for coal but approximately 1.5 times lower than those reported for average Chinese coals and the upper continental crust (UCC). REE contents significantly exceed those of sedimentary (5.36 $\mu\text{g/g}$), mafic (16.77 $\mu\text{g/g}$), and felsic (3.60 $\mu\text{g/g}$) rocks. Elevated Li (30.5 $\mu\text{g/g}$) and Ni (114.4 $\mu\text{g/g}$) concentrations point to a mafic magmatic source, whereas Cu (28.7 $\mu\text{g/g}$) likely originates from basic volcanic rocks such as those of the Dağlıca Complex and the Kemaliye Formation. Chondrite-normalised REE patterns show Dy depletion relative to mafic rocks and Ho depletion compared to sedimentary rocks. Positive δEu anomalies (>1) support a mafic or UCC provenance, while slightly positive δCe values indicate hydrothermal leaching influences. The co-precipitation of Ce with Ca–Mg hydroxides and clay minerals in coal-bearing lacustrine sediments is suggested. Ga enrichment is attributed to aluminium-rich clay minerals and organic matter. Overall, these geochemical signatures reflect combined inputs from hydrothermal leaching and volcanic weathering within a coal-bearing lacustrine environment.

Keywords: bottom ash; strategic elements; rare earth elements (REEs); thermal power plant



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1. Introduction

Within the scope of this study, the concentrations of Critical Raw Materials (CRM2024) and Strategic Raw Materials—including Li, Co, Ni, Cu, Ga, Ge, and Rare Earth Elements (REEs) used in permanent magnets (Nd, Pr, Tb, Dy, Gd, Sm, and Ce), as well as Y—were determined in coal bottom ash samples from the Afşin–Elbistan thermal power plant. The focus of the research is to evaluate which of these elements are geochemically enriched in bottom ash and to investigate their potential sources.

Coal combustion residues, particularly bottom ash, are increasingly recognised as alternative sources for recovering strategic metals. The geochemical composition of these residues reflects the nature of the coal, combustion conditions, and geological inputs from the surrounding environment. Bottom ashes can act as secondary reservoirs for critical elements due to their high concentrations of trace metals and mineral phases, which can retain such elements. This perspective offers a promising opportunity to contribute to the circular economy and reduce dependency on primary raw material imports.

Previous studies have investigated REE and trace metal content in coal and combustion products worldwide, including Chinese coals [1,2], and the geochemical characterisation of global bottom ashes [3–8]. However, systematic studies on Turkish thermal power plant ashes—particularly from Afşin–Elbistan, one of the largest lignite-fired power plants in Türkiye—are limited. Furthermore, comprehensive enrichment assessments based on international reference standards are mainly absent in the region. This study determined the concentrations of Li, Co, Ni, Cu, Ga, Ge, Y, and REEs in thirty bottom ash samples collected from the Afşin–Elbistan thermal power plant. To evaluate the geochemical enrichment and potential sources of these elements, the obtained concentrations were normalised to various geological reference values, including Upper Continental Crust (UCC) [9], Clarke values for coal [10], Chinese coal compositions [1,2], and REE patterns of sedimentary [11], mafic [12], and felsic rocks [13,14]. Additional background data for trace metals were obtained from Turekian and Wedepohl [15] and Vinogradov [16]. A statistical threshold value calculation was also applied to identify anomalous enrichments.

The primary aim of this study is to assess whether the Afşin–Elbistan bottom ashes represent a potential secondary source of strategic elements and to contribute to the global database on the distribution of critical raw materials in coal combustion by-products. The results are evaluated in terms of their implications for future resource recovery and environmental management.

2. Geological and Tectonic Setting

In the Kahramanmaraş region, numerous thrust and fault zones have developed as a result of the closure of the Neotethys Ocean and the subsequent collision between the Arabian Plate and the Tauride Plate [17]. This collision led to the formation of several suture zones in the region [18–25]. Following the subduction of the Neotethys Ocean floor, units of the Tauride Plate were thrust southward over the Arabian Platform, resulting in the development of suture zones and thrust fronts [26,27]. Due to the presence of diverse lithostratigraphic units and the formation of various tectonic slices, the region's geological structure has been classified in different ways. Rigo De Righi and Cortesini [28] divided the tectonic slices in Southeastern Anatolia into four main belts: The Tauride Orogenic Belt, the Border Folds Belt, the Folded Belt, and the Foreland. Based on the geological characteristics of Kahramanmaraş and its surroundings, Yilmaz et al. [29] further subdivided the area into the Orogenic Belt and its sub-belts (Figure 1a).

The oldest geological unit in the study area is the Keban-Malatya Metamorphics, which dates back to the Carboniferous–Permian period and is composed of marble, crystalline limestone, schist, and calcschist. The Maastrichtian unconformably overlies these metamorphic rocks, specifically the Campanian Kemaliye Formation, which consists of conglomerates, sandstones, and shales containing various lithological blocks of different ages (Figure 1b). The underlying Andırın Limestone is tectonically juxtaposed with the Kemaliye Formation. Micritic limestones and cherts represent the Campanian–Turonian Kırızıkandil Formation and are in tectonic contact with the Turonian–Cenomanian Andırın Limestones. Maastrichtian–Campanian Dağlıca Complex is composed of serpentine, peridotite, gabbro, diabase, chert, basic lavas, and limestone blocks within a volcanic matrix.

Above these units lies the Miocene–Pliocene Ahmetçik Formation, which hosts significant coal-bearing deposits. This formation unconformably overlies the older strata and is overlain by Quaternary deposits.

Both limnic and fluvial sedimentary environments characterise the Ahmetçik Formation. The limnic facies are predominantly developed in the central part of the basin and gradually transition into fluvial facies towards the margins. The limnic sequence begins with bluish-grey marl and claystone, progressing upward into alternating layers of lignite and claystone. Lignite is interbedded with gyttja in the upper parts, notably rich in gastropod shells. These layers are occasionally overlain by thick claystone beds containing lignite lenses. At the top of the limnic sequence, grey to brown conglomerates, sandstones, and lacustrine limestones are exposed in the open-pit mining areas. The fluvial facies of the Ahmetçik Formation are mainly represented by conglomerate and sandstone deposits [30–32]. These lithological and tectonic features suggest that the coal-bearing Ahmetçik Formation was deposited in a tectonically active basin where hydrothermal fluid circulation was facilitated by fault and thrust zones. Such structural controls, combined with the lacustrine depositional environment, may have provided favourable conditions for the introduction and enrichment of trace elements within the lignite and associated ashes. The studied bottom ash samples were derived from lignites exploited in the Afşin–Elbistan Basin, which belong to the Miocene–Pliocene Ahmetçik Formation.

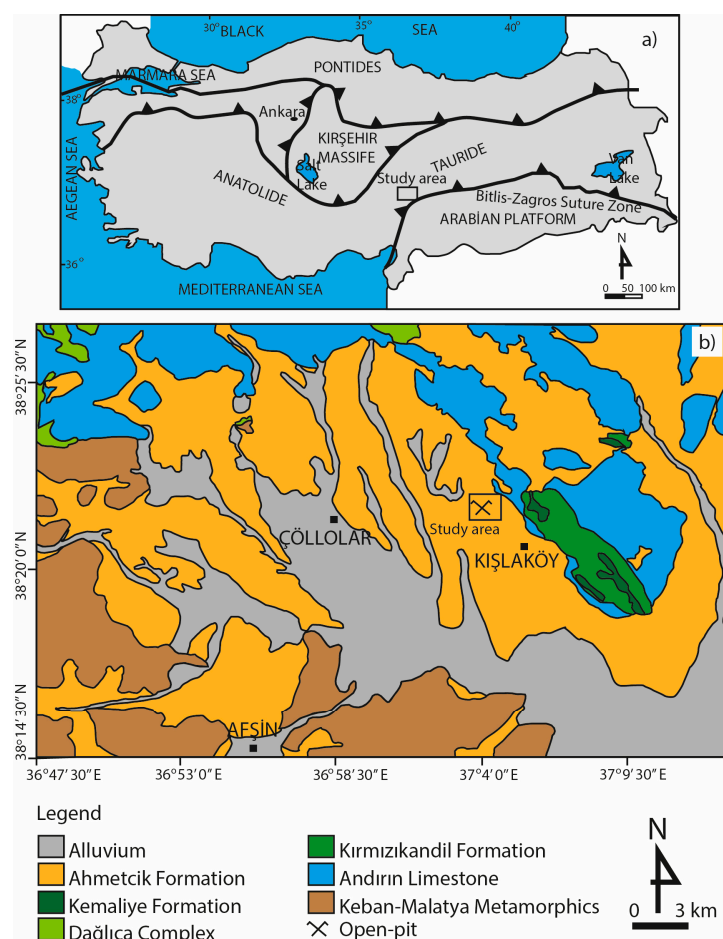


Figure 1. (a) Tectonic map of Türkiye showing major structural zones and sutures [33]. (b) Simplified geological map of the Elbistan Basin and its surroundings. The locations of the Kışlaköy open-pit mine and nearby villages are also shown (modified from [34]).

3. Materials and Methods

In this study, coal bottom ash samples (approximately 2 kg each) were collected from the Afşin–Elbistan Thermal Power Plant. A total of 30 samples (D1–D30) were taken from the bottom ash discharge area. Care has been taken to ensure that the bottom ash sample taken is representative of the specified loading rate. All samples were collected at the burnout rate initially proposed by the Operator. All samples were dried at room temperature and sieved to a –200 mesh size fraction. Fourteen samples were randomly selected from the thirty samples, and XRD (X-Ray Diffractometry) analysis was performed in the MTA Laboratory, Ankara, Türkiye. XRD analyses were performed on powdered bottom ash samples ground to <200 mesh, using CuK α radiation ($\lambda = 1.54059 \text{ \AA}$) with a Ni filter, over a scanning range of $2\text{--}70^\circ 2\theta$, at a scanning speed of $2^\circ/\text{min}$, 33 kV voltage, and 15 mA current. XRD analysis was applied to identify natural minerals that cannot be determined with certainty by optical microscopic methods. Whole-rock samples were analysed for trace elements using ICP-MS (Ion Coupled Plasma-Mass Spectrometry/Agilent 7900) at Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The detailed sample-digesting procedure was as follows: (1) Sample powder (200 mesh) was placed in an oven at 105°C for 12 h of drying; (2) 50 mg of sample powder was accurately weighed and placed in a Teflon digestion vessel (commonly referred to as a Teflon bomb); (3) 1 mL HNO_3 and 1 mL HF were slowly added into the Teflon bomb; (4) Teflon bomb was putted in a stainless steel pressure jacket and heated to 190°C in an oven for $>24 \text{ h}$; (5) After cooling, the Teflon bomb was opened and placed on a hotplate at 140°C and evaporated to incipient dryness, and then 1 mL HNO_3 was added and evaporated to dryness again; (6) 1 mL of HNO_3 , 1 mL of MQ water and 1 mL internal standard solution of $1 \mu\text{g/g}$ In were added, and the Teflon bomb was resealed and placed in the oven at 190°C for $>12 \text{ h}$; (7) The final solution was transferred to a polyethylene bottle and diluted to 100 g by the addition of 2% HNO_3 . GSR-1(GBW07103); A grey medium-grained biotite granite sample was collected from Hunan) GSR-3(GBW07105); An alkali-olivine basalt sample was collected in Hebei) [35,36] according to certified values of chemical composition for rock certified reference materials (CRMs), and JA-2 (andesite) references were used, and test base on GB/T14506.30-2010 [37].

The enrichment coefficients (EC) of the elements in coal bottom ashes will be determined with the element concentrations obtained with the help of the above analysis methods. The EC is defined as the ratio between the concentration of an element in the sample and its corresponding abundance in a reference material, typically the Upper Continental Crust (UCC). In this study, UCC values reported by Taylor and McLennan [38] were used for the calculations:

$$EC_{\text{Element}} = C_{\text{sample}} / C_{\text{UCC}}$$

where C_{sample} is the average concentration of the element in the coal bottom ash samples, and C_{UCC} is its average concentration in the UCC. This coefficient serves as a direct measure of relative enrichment ($EC > 1$) or depletion ($EC < 1$) of each element in the studied material. In coal combustion residues, EC values are beneficial for identifying elements that may have technological or economic significance (e.g., critical REEs), as well as for understanding geochemical processes such as volatilisation, retention in mineral matrices, or incorporation into amorphous phases during combustion EC values are beneficial for identifying elements that may have technological or economic significance (e.g., critical REEs), as well as for understanding geochemical processes such as volatilisation, retention in mineral matrices, or incorporation into amorphous phases during combustion [39,40].

Rare earth element (REE) concentrations were normalized to the Upper Continental Crust (UCC) values to compare relative abundances and to identify geochemical patterns. The normalisation was performed by dividing the concentration of each REE in the sample

by the corresponding UCC reference value according to the method of McLennan [9]. The resulting normalized values were then used to calculate REE ratios such as La_N/Sm_N , Ce_N/Yb_N , La_N/Yb_N , and Gd_N/Yb_N , which help infer the dominant source rocks contributing to the studied samples. The δEu value was calculated using Equation (1) to determine the degree of europium anomaly. This value helps identify provenance, assess diagenetic conditions, and classify rock types. In this study, the normalisation values for Eu_N , Sm_N , and Gd_N were based on the average compositions of sedimentary rocks (clays and shales), mafic rocks, and felsic rocks [11–13], respectively. The enrichment of rare earth elements (REEs) in sedimentary rocks is often attributed to the weathering of source rocks. The composition of the source rocks typically controls whether Eu anomalies are positive or negative. Therefore, the δEu value can indicate the REE provenance in coal samples.

$$\delta Eu = Eu/Eu^* = 2Eu_N/Sm_N + Gd_N \quad (1)$$

The δCe value was calculated using Equation (2). Cerium is redox-sensitive and can readily oxidise or reduce depending on environmental conditions [2,41]. A negative Ce anomaly often indicates a marine sedimentary provenance [2].

$$\delta Ce = Ce/Ce^* = 2Ce_N/La_N \times Pr_N \quad (2)$$

In this study, δEu and δCe values were calculated using both UCC-normalised data (from McLennan [9], revised from Taylor and McLennan [38]) and normalised values based on sedimentary rocks [11], mafic rocks [12], and felsic rocks [13].

The spider patterns were normalised according to the calculated threshold values (Equation (3)), where μ is the mean concentration of the element and σ is its standard deviation.

$$\text{Threshold Value} = \text{Arithmetic Mean } (\mu) + 2 \times \text{Standard Deviation } (\sigma) \quad (3)$$

4. Results

4.1. Petrography

In 30 coal bottom ashes from the Afşin–Elbistan thermal power plant, the percentage moisture and ash content were determined to be a minimum of 3.92%–6.28%, and 23.58%–66.28%, respectively. In this study, the mineralogical composition of 15 representative bottom ash samples (D1–D25) was determined using X-ray diffraction (XRD) analysis (Table 1, Figure 2). The XRD results revealed four main mineralogical groups across the bottom ash samples: Hydration products: Portlandite ($Ca(OH)_2$), ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$], calcite ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), and anhydrite ($CaSO_4$). High-temperature phases: Akermanite ($Ca_2MgSi_2O_7$), gehlenite [$Ca_2Al(AlSiO_7)$], larnite (β - Ca_2SiO_4), and lime (CaO). Silica and feldspar group minerals: Quartz (SiO_2), plagioclase, and alkali feldspar (Na-, K-, and Ca-rich aluminosilicates). Natural carbonates: Dolomite [$CaMg(CO_3)_2$], detected only in sample D4. Hydration products such as portlandite, ettringite, calcite, gypsum, and anhydrite are generally formed during post-combustion exposure of bottom ash to atmospheric moisture or water. Free lime (CaO), upon contact with water, typically converts to portlandite, whereas ettringite, gypsum, and calcite result from aqueous reactions among calcium, aluminium, and sulfate ions. The presence of these phases indicates the potential for cementitious behaviour in the bottom ash [42,43]. High-temperature mineral phases—akermanite, gehlenite, larnite, and lime—form during coal combustion at temperatures exceeding 1000 °C. These phases, particularly calcium silicates, result from reactions between lime and clay minerals under high-temperature conditions. Lime (CaO), a common component in bottom ash, often hydrates to form portlandite upon water exposure [44,45]. Quartz, plagioclase, and alkali

feldspar are interpreted as either residual refractory phases originating from clay minerals in the parent coal or as newly formed crystalline phases following thermal alteration. Quartz is highly resistant to thermal decomposition and is typically the most abundant silicate phase in coal bottom ash. Dolomite ($\text{CaMg}(\text{CO}_3)_2$) was identified exclusively in sample D4 and likely originates from carbonate-rich constituents in the original coal. Under high-temperature conditions, dolomite can decompose to form CaO and MgO [46].

Table 1. Mineralogical composition of the studied bottom ashes, as determined by XRD results.

Mineral	D1	D2	D3	D4	D5	D11	D12	D13	D14	D15	D21	D22	D23	D24	D25
Portlandite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Ettringite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Calcite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Quartz	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Anhydrite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Gypsum	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Akermanite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Gehlenite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Larnite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Plagioclase	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Alkali Feldspar	+	+	+	+	+	+	+	+	+	+	—	+	—	—	+
Lime	+	+	+	+	+	+	+	+	+	+	+	—	+	+	+
Dolomite	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—

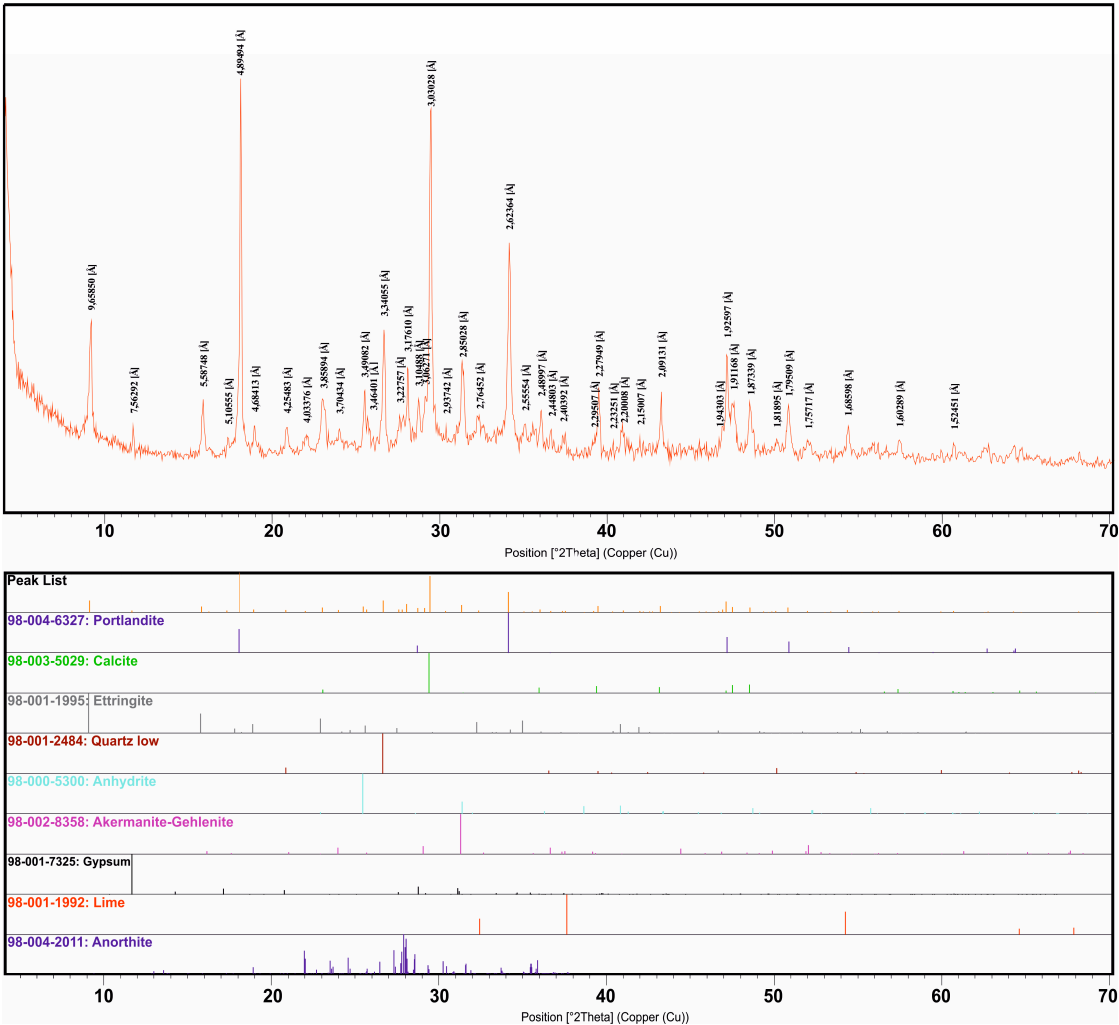


Figure 2. XRD pattern of the bottom ash sample (D11) showing the identified mineral phases.

Although detailed microscopic characterisation (e.g., SEM or optical microscopy) was not conducted in this study, previous investigations on coal bottom ash have shown that such materials typically consist of angular to sub-rounded particles with heterogeneous textures, including glassy matrices and crystalline inclusions [42,44]. Porous and vesicular morphologies reported in the literature are commonly associated with rapid cooling and volatile release during combustion. These features may influence the adsorption and retention behaviour of strategic elements such as REEs, Li, and Ge. In particular, the presence of Ca-rich phases, such as portlandite and ettringite, as identified by XRD, suggests a potential for secondary reactions in aqueous environments, which can affect the mobility and environmental risk of these elements.

Figure 3 provides representative field and process images related to lignite seams, combustion, and ash handling in the Afşin–Elbistan Thermal Power Plant study. In Figure 3a, the stratified lignite seams are interbedded with lighter-coloured clay and carbonate layers, reflecting changes in depositional facies within the lacustrine environment. These coal seams constitute the primary feedstock for combustion. Figure 3b presents the bottom ash discharge area inside the plant (floor view), where ash is handled, and the study samples were collected. Figure 3c shows the combustion chamber, where coal is burned at high temperatures typical for lignite-fired thermal power plants. During this process, organic components are volatilized, while inorganic elements—including rare earth elements and other strategic metals—become enriched in the residual bottom ash. Together, these images provide context for the stratigraphic setting of lignite seams, the combustion process, and the formation of the ash materials analysed in this study.



Figure 3. Field and process images related to coal combustion and bottom ash formation: (a) Outcrop of layered lignite seams with alternating clay and carbonate levels, reflecting depositional facies

changes in the open-pit mine; (b) Bottom ash discharge area inside the thermal power plant (floor view), where study samples were collected; (c) Combustion chamber showing high-temperature coal burning and ash formation.

4.2. Geochemistry

In this study, the elements listed in Table 2 include several that are classified as strategic raw materials. The concentrations of Li, Co, Ni, Cu, Ga, Ge, and REEs varied considerably among the 30 bottom ash samples. In general, Ni and Co displayed relatively higher concentrations compared to other strategic elements, whereas HREEs (e.g., Yb, Lu) showed lower values.

Table 2. Chemical composition of REE in the studied bottom ashes. All values are in µg/g.

Samples	Li	Co	Ni	Cu	Ga	Ge	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
D1	29.1	14.9	117	28.6	11.8	1.07	21.9	38.7	4.4	16.7	3.3	0.78	2.92	0.45	2.53	0.52	1.44	0.22	1.39	0.21	14.4
D2	29.9	14.7	111	28.4	11.5	1.06	21.8	37.8	4.3	16.3	3.2	0.75	2.85	0.45	2.68	0.54	1.55	0.23	1.51	0.23	15.1
D3	30.2	14.8	115	29.0	12.0	1.08	22.4	38.5	4.4	17.0	3.4	0.77	2.80	0.44	2.68	0.52	1.48	0.21	1.41	0.21	14.5
D4	30.2	14.5	113	28.5	11.7	1.08	22.2	39.0	4.4	16.9	3.4	0.78	2.88	0.45	2.63	0.51	1.49	0.22	1.40	0.22	14.3
D5	30.5	14.9	115	28.2	11.6	1.09	22.2	39.3	4.5	16.9	3.4	0.78	2.87	0.44	2.74	0.52	1.45	0.21	1.39	0.21	15.0
D6	31.0	14.6	109	28.3	11.5	1.11	21.4	39.1	4.4	16.8	3.4	0.76	2.79	0.44	2.56	0.52	1.43	0.22	1.42	0.22	14.4
D7	30.5	14.5	113	28.3	11.5	1.09	21.4	38.0	4.3	16.7	3.2	0.76	2.82	0.43	2.60	0.51	1.42	0.21	1.36	0.21	14.1
D8	31.1	15.0	116	29.2	11.9	1.14	22.6	39.6	4.6	17.3	3.3	0.78	2.92	0.45	2.73	0.52	1.50	0.22	1.44	0.22	15.1
D9	30.2	14.7	113	29.0	11.8	1.10	21.9	38.6	4.5	16.8	3.3	0.76	2.78	0.44	2.59	0.52	1.42	0.21	1.34	0.21	14.4
D10	29.7	14.6	114	28.6	11.8	1.14	22.2	38.2	4.5	17.1	3.3	0.80	2.85	0.45	2.67	0.53	1.47	0.22	1.42	0.21	14.7
D11	30.6	15.0	116	29.1	11.7	1.14	21.5	38.5	4.5	17.1	3.5	0.80	2.87	0.45	2.56	0.51	1.48	0.21	1.37	0.21	14.7
D12	30.6	14.7	111	29.2	11.5	1.07	21.6	38.3	4.5	16.6	3.3	0.78	2.81	0.45	2.60	0.52	1.44	0.21	1.36	0.21	14.6
D13	29.9	14.4	113	28.2	11.6	1.07	21.0	37.8	4.2	16.3	3.2	0.74	2.76	0.44	2.59	0.50	1.39	0.21	1.31	0.21	14.2
D14	29.7	14.4	116	29.0	11.5	1.05	21.7	38.1	4.4	16.7	3.3	0.77	2.81	0.45	2.64	0.50	1.41	0.21	1.37	0.21	14.6
D15	30.5	14.7	113	28.6	11.7	1.08	22.2	38.7	4.5	17.2	3.5	0.78	2.82	0.45	2.57	0.52	1.46	0.21	1.39	0.21	14.5
D16	30.8	14.3	116	28.2	11.4	1.08	22.0	38.5	4.5	17.1	3.4	0.77	2.80	0.45	2.55	0.52	1.48	0.22	1.39	0.21	14.5
D17	30.4	14.7	113	28.3	11.4	1.07	22.0	39.0	4.5	17.1	3.4	0.80	2.90	0.47	2.65	0.53	1.45	0.22	1.40	0.21	15.0
D18	29.6	14.2	110	28.2	11.1	1.02	21.3	38.1	4.4	16.5	3.2	0.76	2.68	0.45	2.53	0.52	1.40	0.22	1.36	0.21	14.2
D19	30.2	14.3	114	27.9	11.6	1.04	21.3	38.3	4.4	16.7	3.3	0.76	2.79	0.45	2.61	0.51	1.41	0.21	1.36	0.21	14.7
D20	30.6	14.7	114	28.1	11.1	1.01	21.6	38.6	4.5	16.6	3.3	0.78	2.92	0.45	2.68	0.56	1.50	0.22	1.39	0.22	15.5
D21	31.5	15.3	119	29.3	12.1	1.07	22.5	40.0	4.6	17.5	3.4	0.83	2.98	0.47	2.76	0.55	1.52	0.23	1.45	0.23	15.9
D22	29.7	14.3	111	28.8	11.4	1.02	22.0	38.9	4.4	16.7	3.3	0.78	2.95	0.44	2.57	0.52	1.44	0.22	1.41	0.22	14.6
D23	30.6	14.7	115	28.8	11.7	1.04	22.5	39.9	4.5	17.1	3.3	0.80	2.94	0.45	2.64	0.53	1.46	0.22	1.39	0.21	14.9
D24	30.8	14.8	117	29.8	12.0	1.07	22.0	39.0	4.5	16.8	3.2	0.78	2.89	0.43	2.61	0.53	1.47	0.22	1.39	0.22	14.8
D25	30.5	14.6	115	28.3	11.5	1.08	22.4	38.9	4.4	17.0	3.2	0.78	2.93	0.45	2.55	0.51	1.45	0.21	1.39	0.22	14.6
D26	30.8	15.0	115	28.6	11.8	1.08	22.0	38.9	4.4	16.8	3.3	0.80	2.88	0.44	2.61	0.52	1.44	0.21	1.36	0.21	14.3
D27	32.2	15.1	118	29.2	12.0	1.09	22.6	39.8	4.6	17.4	3.4	0.84	2.96	0.44	2.62	0.52	1.46	0.21	1.40	0.22	15.0
D28	31.7	15.2	117	29.1	11.8	1.08	22.6	40.4	4.6	17.3	3.4	0.81	3.07	0.46	2.71	0.53	1.50	0.22	1.44	0.22	15.4
D29	31.6	15.1	121	29.3	12.1	1.05	22.8	39.3	4.5	16.9	3.3	0.82	2.89	0.44	2.67	0.50	1.45	0.22	1.43	0.21	14.8
D30	30.8	14.7	115	28.5	11.7	1.07	22.1	39.4	4.5	17.0	3.3	0.78	2.88	0.44	2.66	0.52	1.46	0.22	1.39	0.21	14.9
Mean	30.5	14.7	114.4	28.7	11.7	1.1	22.0	38.8	4.5	16.9	3.3	0.8	2.9	0.4	2.6	0.5	1.5	0.2	1.4	0.2	14.72
Standard Dev.	0.68	0.27	2.68	0.47	0.25	0.03	0.46	0.67	0.08	0.30	0.08	0.02	0.08	0.01	0.06	0.01	0.04	0.01	0.04	0.01	0.40
Median	30.5	14.7	114.6	28.6	11.7	1.1	22.0	38.8	4.5	16.9	3.3	0.8	2.9	0.4	2.6	0.5	1.5	0.2	1.4	0.2	14.5
Clarke Value	12	5.1	13	16	5.8	1.6	11	23	3.4	12	2	0.43	2.7	0.32	2.1	0.57	1	0.3	1	0.2	
Coal	32	7.1 _a	13.7 _a	18.4 _a	94.80 _b	15.66 _b	22.5	46.7	3.42	22.3	4.07	0.84	4.65	0.62	3.74	0.96	1.79	0.64	2.08	0.38	
UCC	20.0	17.0	44.0	25.0	17.0	1.6	30.0	64.0	7.1	26.0	4.5	0.9	3.8	0.6	3.5	0.8	2.3	0.3	2.2	0.3	
Sedimentary Rocks	3	20	95	57	30	1	1	2	0.27	0.9	0.2	0.04	0.18	0.03	0.12	0.4	0.09	0.016	0.1	0.017	
Mafic Rocks	1	48	130	87	17	1.3	1	4.25	0.53	2.6	0.8	0.32	1.21	0.21	3.8	0.28	0.88	0.12	0.63	0.14	
Felsic Rocks	5.5	5	8	20	20	1.4	1	1.58	0.2	0.62	0.1	0.0094	0.057	0.003	0.018	0.0034	0.009	0.0016	0.0035	0.0008	
Threshold Value	31.87	15.27	119.81	29.63	12.16	1.14	22.89	40.15	4.62	17.49	3.48	0.82	3.02	0.47	2.75	0.55	1.53	0.23	1.47	0.22	

Average REE patterns in sedimentary rocks were taken from Haskin and Gehl [11], while mafic and felsic rock patterns were taken from Frey and Haskin [12] and Haskin and Gehl [13], respectively. Values for Chinese coals were taken from [1,2,14]. Clarke values for coal were adopted from Yudovich and Ketris [10], a values from Finkelman [47], and b values from [43]. Upper Continental Crust (UCC) values were taken from McLennan [9] and revised by Taylor and McLennan [38]. The average contents of Li, Co, Ni, Cu, Ga, and Ge in sedimentary, mafic, and felsic rocks were taken from [15,16].

5. Discussion

5.1. Mineral Composition of the Coal Ash

XRD analyses of the studied bottom ash samples (Table 1) show a mineral assemblage dominated by portlandite, ettringite, calcite, quartz, anhydrite, and gypsum. These minerals are typical combustion products and hydration/sulfate phases formed during cooling and storage [48]. In addition, high-temperature Ca–Al–Si silicate phases such as akermanite, gehlenite, and larnite were detected, which are commonly produced during the reaction of aluminosilicate and carbonate minerals under boiler conditions [46,49]. Feldspars (plagioclase and alkali feldspar) were also identified and represent primary detrital minerals inherited from the original coal and associated sediments [50]. Minor amounts of lime and dolomite were recorded in some samples. Overall, the mineral composition of the Afşin–Elbistan bottom ash reflects a mixture of high-temperature combustion minerals (e.g., portlandite, ettringite, larnite, akermanite, gehlenite) and primary terrigenous phases (e.g., quartz, feldspars, calcite, dolomite). This mineralogical association highlights the complex transformation of inorganic constituents during combustion as well as the partial preservation of the original mineral matter [48].

5.2. Geochemical Distribution of REEs

Rare earth elements are commonly subdivided into light rare earth elements (LREEs: La, Ce, Pr, Nd, Pm) and heavy rare earth elements (HREEs: Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). The contents of light and heavy rare earth elements were determined in the studied deep coal ash samples. The total concentration of each element is expressed as ΣREE . The L/H ratio indicates the distribution difference between light and heavy rare earth elements. The estimated values of $\Sigma\text{LREE} = 82.2 \mu\text{g/g}$ and $\Sigma\text{HREE} = 3.3 \mu\text{g/g}$ from the thirty bottom coal ash samples were used to calculate the L/H ratio. This indicates that light rare earth elements (LREEs) are enriched relative to heavy rare earth elements (HREEs) by a factor of 24.85, calculated as the ratio of ΣLREE to ΣHREE .

The calculated total REE + Y concentration was $111 \mu\text{g/g}$. In comparison, a total $\Sigma\text{REE} + \text{Y}$ value of $136 \mu\text{g/g}$ was reported in Chinese coals by Dai et al. [2]. The total REE + Y content in the studied bottom ashes is thus $25 \mu\text{g/g}$ lower than in Chinese coals. The average total REE content in the studied samples is $96.7 \mu\text{g/g}$, which is similar to the background value for coal ($96.42 \mu\text{g/g}$), based on data from Yudovich and Ketris [10], but is approximately 1.5 times lower than the average total REE content in the Upper Continental Crust (UCC) ($146.4 \mu\text{g/g}$). These results indicate that the studied samples are consistent with the Clarke value for coal but are depleted relative to the Universal Coal Curve. REE chondrite normalised patterns show that LREE and MREE are enriched compared to HREE (Figure 4a). This pattern reflects a natural fractionation during sedimentation or coal formation and may be inherited from the source rocks. Considering the Figure 4b REE pattern, it can be said that UCC source elements are enriched in the studied coal ashes.

The total REE values in the samples are significantly higher than those found in sedimentary rocks, mafic rocks, and felsic rocks ($5.36 \mu\text{g/g}$, $16.77 \mu\text{g/g}$, and $3.60 \mu\text{g/g}$, respectively). Budakoğlu et al. [51] studied the REE composition of surface and shallow core lake sediments and reported average total REE contents of 78.7, 50.2, 50.2, and $55.5 \mu\text{g/g}$. The REE content of the studied bottom ash samples ($96.7 \mu\text{g/g}$) is higher than these values. REE concentrations were normalised to UCC values, and ratios such as $\text{La}_\text{N}/\text{Sm}_\text{N}$, $\text{Ce}_\text{N}/\text{Yb}_\text{N}$, $\text{La}_\text{N}/\text{Yb}_\text{N}$, and $\text{Gd}_\text{N}/\text{Yb}_\text{N}$ (ranging from 0.76 to 1.14) indicate a dominant contribution from mafic source rocks [9].

These ratios also suggest that LREEs are more mobile and/or retained during combustion and ash formation, supporting selective enrichment.

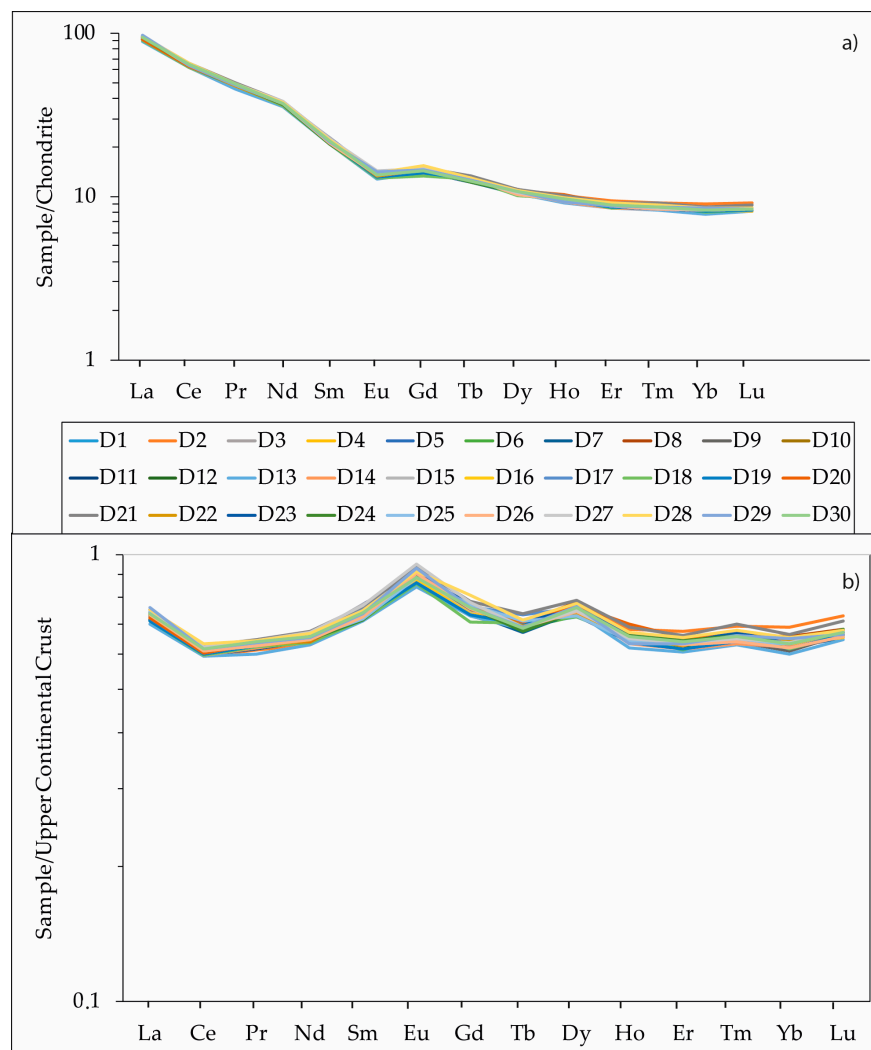


Figure 4. The diagram shows the chondrite normalised pattern, (a) The average chondrite crust normalisation pattern [52], (b) Upper continental crust normalisation pattern [38].

Table 3 presents the estimated δEu_N and δCe_N values. The δEu values range from 0.12 to 2.03 (based on Equation (1)). A δEu value greater than 1 indicates a moderate to vigorous positive europium anomaly. These values suggest that the europium source is geochemically similar to the composition of the UCC and mafic rock. This is further supported by the relatively high concentrations of Li (30.5 $\mu\text{g/g}$) and Ni (114.4 $\mu\text{g/g}$), which are commonly associated with mafic and ultramafic rocks.

Table 3. Calculated δEu_N and δCe_N values.

Normalisation	Calculated Values	Normalisation	Calculated Values
$\delta\text{Eu}_N(\text{UCC})$	1.18	$\delta\text{Ce}_N(\text{UCC})$	0.89
$\delta\text{Eu}_N(\text{Sedimentary Rocks})$	0.12	$\delta\text{Ce}_N(\text{Sedimentary Rocks})$	1.06
$\delta\text{Eu}_N(\text{Mafic Rocks})$	0.75	$\delta\text{Ce}_N(\text{Mafic Rocks})$	0.60
$\delta\text{Eu}_N(\text{Felsic Rocks})$	2.03	$\delta\text{Ce}_N(\text{Felsic Rocks})$	1.11

It is likely that bottom ash material derived from the upper crust or altered rock sources along structural zones was incorporated into the lignite during its formation in the Afşin–Elbistan basin. This scenario is consistent with the occurrence of Eu as a diadochic element in calcium-rich plagioclase within mafic rocks and its subsequent incorporation into sedimentary structures under varying geochemical conditions. Yuan et al. [39] reported that

Eu^{3+} is prone to leaching under increasing soil acidity and weathering intensity, indicating its relatively high mobility. As such, europium can be enriched in clay minerals formed by altering rocks in oxidised environments.

The estimated δCe values offer additional insight into the redox conditions during coal formation. Under oxidising conditions, Ce^{3+} in connate water can be oxidised to Ce^{4+} and separated from other REEs. In contrast, under anoxic conditions, Ce retains its trivalent state [39,41,53]. Ce values were normalised to La and Pr, and δCe was calculated accordingly. The light REE content in coal ashes is significantly higher than that of heavy REEs, which likely influenced the calculated δCe values. Although the Ce concentration in the studied samples (38.8 $\mu\text{g/g}$) is lower than in Chinese coals and UCC (both $\sim 64 \mu\text{g/g}$), it remains higher than the average values for the Clarke value of coal, sedimentary, mafic, and felsic rocks. A positive Ce anomaly typically indicates oxidising conditions [54]. Ce is known to associate with Fe- and Mn-oxides [55], where Mn^{4+} can act as an electron acceptor, promoting the oxidation of Ce^{3+} to Ce^{4+} [56,57]. Such oxidation pathways can lead to Ce enrichment in ash, particularly if Fe–Mn oxide phases are retained post-combustion.

The average Ce in world coal ashes is 130 [58], while the Ce content in Afşin–Elbistan bottom coal ashes is approximately 3.35 times lower. The Ce content in these samples may reflect post-depositional remobilisation or fractionation during combustion.

Figure 5 shows that the compositions of sedimentary and felsic rocks have influenced the bottom ash samples, with notable negative anomalies of Ho and Dy in sedimentary and mafic magmatic rocks, respectively. The sedimentological and structural characteristics of the basin suggest a sedimentary source for the REE elements. The normalised Y and Ho values in coal primarily reflect geochemical processes in the sediment source rocks, sedimentary environments, and hydrothermal fluids [59,60].

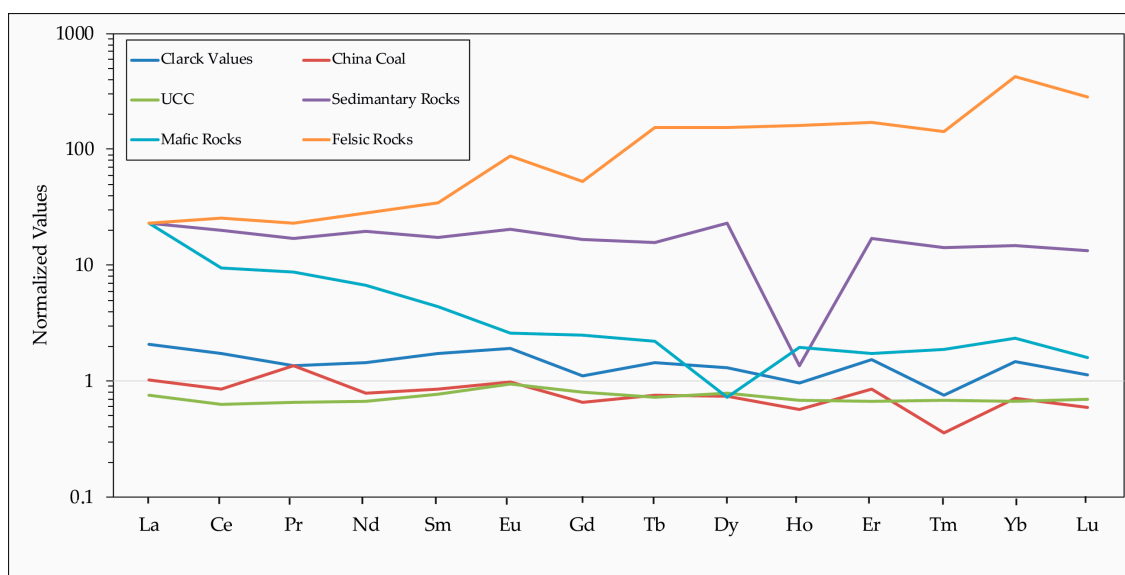


Figure 5. Normalised distribution patterns of rare earth elements (REEs) in bottom ash samples from the Afşin–Elbistan Thermal Power Plant, compared with reference values for UCC, Clarke values, China coals, and mafic, felsic, and sedimentary rocks.

The average normalised values of Y (14.7 $\mu\text{g/g}$ in the studied samples vs. 30 $\mu\text{g/g}$ in sedimentary rocks) and Ho (0.55 $\mu\text{g/g}$ vs. 0.4 $\mu\text{g/g}$), and their ratio ($Y_N/\text{Ho}_N = 0.49/0.71 = 0.69$)—which is less than 1—indicate a significant influence from sedimentary sources. According to Fu et al. [61], the Y content in High-Ge-bearing coal is significantly higher than in Low-Ge-bearing coal fields. In the Afşin–Elbistan coals, the moderate Y content suggests a limited association with Ge, further indicating a mixed sedimentary-mafic origin.

Although the combustion process may cause partial redistribution or mineralogical incorporation of REEs, many studies have shown that their normalised patterns and geochemical ratios often retain provenance and redox signals post-combustion, especially when the ash formation temperatures are below the volatilisation points of REEs [62,63]. In our samples, the preservation of distinct LREE/HREE fractionation, positive δEu anomalies, and Ce redox sensitivity indicates that combustion has not fully masked the original geochemical signatures. Moreover, REEs in bottom ash tend to be hosted in stable silicate or phosphate phases (e.g., monazite, xenotime), which further supports the retention of primary geochemical characteristics. These results suggest that REE parameters in the studied bottom ashes remain meaningful for interpreting source rock composition and depositional redox environments.

5.3. Enrichment Coefficients of REEs and Y

In geochemical studies, enrichment coefficients (EC) are frequently used to evaluate the degree of elemental accumulation or depletion in solid samples relative to a standard reference material. In this study, EC values for rare earth elements (REEs) and yttrium (Y) were calculated to assess their quantitative geochemical behaviour in coal bottom ash.

In this study, the calculated EC values for all REEs and Y were below 1, indicating a general depletion of these elements in bottom ash samples relative to UCC levels. The highest enrichment coefficients were observed for Eu (0.90), Gd (0.89), and Sm (0.81), suggesting a relatively higher stability or retention of these middle REEs under combustion conditions. In contrast, the lowest EC values were recorded for Y (0.49), Yb (0.50), and Lu (0.52), indicating a more substantial depletion of heavy REEs, which may be attributed to their lower condensation temperatures and/or higher volatility during coal combustion [60]. Additionally, the observed differentiation may also reflect the primary REE distribution in the original bulk coals.

These enrichment patterns are clearly illustrated in the normalised distribution diagrams of the studied bottom ash samples (Figures 5 and 6), which are compared with reference values for UCC, Clarke value of coal, Chinese coals, and mafic, felsic, and sedimentary rocks. This comparison provides additional quantitative support for interpreting the geochemical behaviour and resource potential of strategic elements in coal ash.

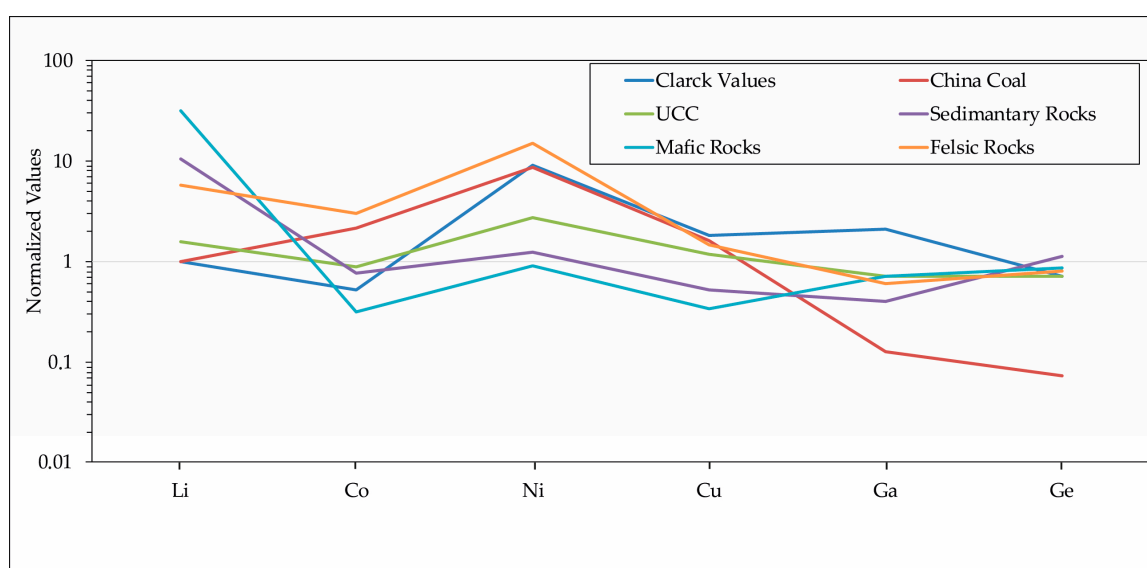


Figure 6. Normalised distribution patterns of strategic metals (Li, Co, Ni, Cu, Ga, and Ge) in bottom ash samples from the Afşin–Elbistan Thermal Power Plant, compared with reference values for UCC, Clarke values, China coals, and mafic, felsic, and sedimentary rocks.

5.4. Geochemical Distribution of Li, Ni, Cu, Co, Ga and Ge

The concentrations of strategic elements such as Cu (28.7 µg/g), Ni (114.4 µg/g), and Co (14.7 µg/g) in the Afşin–Elbistan bottom ash samples are significantly higher than both the Clarke values for coal and the average values reported in Chinese coals [61]. These values suggest moderate to strong enrichment, as further supported by the calculated enrichment coefficients (EC), which exceed unity for Ni, Co, Cu, and Ga (Table 4). The enrichment of these elements is likely influenced by magmatic inputs and hydrothermal processes affecting the original sedimentary units. Figure 6 illustrates the distribution pattern, highlighting relatively elevated Ga levels and lower Ge concentrations compared to the other elements.

Table 4. Enrichment coefficients (EC) of rare earth elements and yttrium in bottom ash samples relative to Upper Continental Crust (UCC) values [38].

Element	Avg. Concentration (µg/g)	UCC Value (µg/g)	EC (Enrichment Coefficient)
La	21.50	30.00	0.72
Ce	38.80	64.00	0.61
Pr	4.60	7.10	0.65
Nd	17.20	26.00	0.66
Sm	3.80	4.70	0.81
Eu	0.90	1.00	0.90
Gd	3.40	3.80	0.89
Tb	0.50	0.64	0.78
Dy	2.90	4.20	0.69
Ho	0.55	0.87	0.63
Er	1.20	2.30	0.52
Tm	0.18	0.33	0.55
Yb	1.10	2.20	0.50
Lu	0.17	0.33	0.52
Y	14.70	30.00	0.49
Li	30.50	20.00	1.52
Co	14.70	17.00	0.86
Ni	114.5	44.00	2.60
Cu	28.7	25.00	1.14
Ga	11.70	17.00	0.68
Ge	1.10	1.60	0.67

The average concentration of Ge in the bottom ash samples (1.1 µg/g) is notably higher than that of the original lignite samples from the Afşin–Elbistan Basin (0.57 µg/g), as reported by Cicioğlu Sütçü and Karayığit [50]. This observation implies that Ge is relatively resistant to volatilisation during combustion under sub-oxidising and reducing boiler conditions. Supporting this, Fu et al. [61] emphasised that Ge enrichment in coal ash is commonly associated with calcite, which may protect Ge from volatilisation. In contrast, Ga is more closely linked with insoluble phases such as iron and manganese oxides, organic matter, pyrite, kaolinite, illite, and quartz [58,62].

5.5. Characteristics of the Geochemical Element Distribution in the Bottom Ashes

A low positive correlation ($r = 0.33$) exists between Ge and Co in the Afşin–Elbistan bottom ashes. The presence of high positive correlations between Co and Ni ($r = 0.68$) and between Co and Cu ($r = 0.62$), Co and Ga ($r = 0.69$), Cu and Ga ($r = 0.69$), Ni and Ga ($r = 0.69$) suggest that they were enriched from the same source and were enriched in aluminium-rich clay minerals (Table 5).

Table 5. Pearson correlation relationship between REE and Li, Co, Cu, Ni, Ga, Ge in bottom ashes ($p = 0.05$ significance).

	Li																			
Li	1.00	Co																		
Co	0.67	1.00	Ni																	
Ni	0.5	0.68	1.00	Cu																
Cu	0.41	0.62	0.55	1.00	Ga															
Ga	0.43	0.69	0.69	0.68	1.00	Ge														
Ge	0.20	0.33	0.15	0.22	0.45	1.00	La													
La	0.50	0.64	0.60	0.49	0.61	0.18	1.00	Ce												
Ce	0.71	0.69	0.49	0.42	0.46	0.09	0.74	1.00	Pr											
Pr	0.64	0.56	0.45	0.41	0.32	0.16	0.69	0.76	1.00	Nd										
Nd	0.61	0.61	0.55	0.42	0.56	0.43	0.75	0.73	0.81	1.00	Sm									
Sm	0.38	0.43	0.19	0.28	0.26	0.36	0.39	0.43	0.58	0.72	1.00	Eu								
Eu	0.67	0.74	0.66	0.53	0.50	0.10	0.71	0.71	0.69	0.75	0.49	1.00	Gd							
Gd	0.49	0.67	0.51	0.40	0.34	0.02	0.66	0.77	0.51	0.56	0.28	0.72	1.00	Tb						
Tb	0.06	0.19	0.12	−0.02	−0.12	−0.03	0.31	0.26	0.36	0.41	0.33	0.36	0.35	1.00	Dy					
Dy	0.37	0.53	0.37	0.24	0.33	0.09	0.50	0.44	0.43	0.36	0.21	0.35	0.44	0.36	1.00	Ho				
Ho	0.14	0.30	−0.01	0.02	−0.14	−0.24	0.25	0.29	0.35	0.18	0.13	0.28	0.42	0.47	0.42	1.00	Er			
Er	0.33	0.50	0.25	0.27	0.24	0.19	0.51	0.35	0.38	0.42	0.32	0.38	0.54	0.45	0.55	0.65	1.00	Tm		
Tm	0.14	0.29	0.04	0.19	0.06	−0.19	0.39	0.41	0.30	0.25	0.15	0.33	0.45	0.52	0.40	0.73	0.68	1.00	Yb	
Yb	0.27	0.41	0.17	0.25	0.26	0.10	0.56	0.36	0.30	0.35	0.24	0.33	0.48	0.43	0.55	0.55	0.82	0.80	1.00	Lu
Lu	0.25	0.36	0.04	0.24	0.13	−0.02	0.32	0.30	0.23	0.17	0.14	0.23	0.41	0.38	0.47	0.62	0.76	0.77	0.82	1.00

clearly distinguishable in the XRD spectra, may be present in very low amounts and could represent either inherited refractory minerals from the parent coal or recrystallised phases after combustion. These silicates can act as inert carriers or weak sorbents for elements such as Li^+ , Ga^{3+} , and Co^{2+} under high-temperature conditions [40]. In particular, Li has been reported to substitute into feldspar and clay mineral structures, suggesting that its enrichment in the ash may be partially mineral-hosted [43]. Gypsum and anhydrite, sulfate phases formed during late-stage diagenesis or combustion-related oxidation, may also play a role in trace element retention. Sulfate minerals are often associated with the secondary immobilisation of elements like Cu and Co, particularly under oxidising conditions. The co-occurrence of sulfate phases and elevated Co and Cu concentrations further supports this interpretation. On the other hand, Ge shows relatively low correlations with different elements and may be hosted in discrete phases such as calcite, as suggested by Fu et al. [61].

6. Conclusions

This study provides a comprehensive mineralogical and geochemical characterisation of bottom ash from the Afşin–Elbistan thermal power plant, with a focus on strategic elements. The ashes are primarily composed of hydration products and high-temperature calcium silicates, together with inherited terrigenous minerals such as quartz and feldspars. This highlights the combined effects of combustion processes and primary mineral inputs on the final mineralogical composition.

Geochemically, the bottom ash shows light REE enrichment relative to heavy REEs, accompanied by characteristic fractionation and anomalies that indicate partial preservation of source signatures and redox-related processes during combustion. Enrichment of critical elements such as Co, Ni, Cu, Ga, and Li, along with their correlations and mineral affinities, underscores the potential of bottom ash as a secondary resource.

Overall, the findings provide new insights into the mineralogical transformations and geochemical behaviour of strategic elements during lignite combustion, while emphasising both the resource potential and the environmental implications of coal-derived bottom ash.

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References

- Dai, S.; Li, D.; Chou, C.-L.; Zhao, L.; Zhang, Y.; Ren, D.; Ma, Y.; Sun, Y. Mineralogy and geochemistry of boehmite-rich coals: New insights from the Haerwusu Surface Mine, Jungar Coalfield, Inner Mongolia, China. *Int. J. Coal Geol.* **2007**, *74*, 185–202. [\[CrossRef\]](#)
- Dai, S.; Ren, D.; Chou, C.-L.; Finkelman, R.B.; Seredin, V.V.; Zhou, Y. Geochemistry of trace elements in Chinese coals: A review of abundances, genetic types, impacts on human health, and industrial utilization. *Int. J. Coal Geol.* **2012**, *94*, 3–21. [\[CrossRef\]](#)
- Zou, J.; Han, F.; Li, T.; Tian, H.; Li, Y. Mineralogical and geochemical compositions of the Lopingian coals in the Zhongliangshan Coalfield, Southwestern China. *Minerals* **2018**, *8*, 104. [\[CrossRef\]](#)
- Zou, J.; Cheng, L.; Guo, Y.; Wang, Z.; Tian, H.; Li, T. Mineralogical and geochemical characteristics of lithium and rare earth elements in high-sulfur coal from the Donggou mine, Chongqing, Southwestern China. *Minerals* **2020**, *10*, 627. [\[CrossRef\]](#)
- Liu, J.; Song, H.; Dai, S.; Nechaev, V.P.; Graham, I.T.; French, D.; Nechaeva, E.V. Mineralization of REE-Y-Nb-Ta-Zr-Hf in Wuchiapingian coals from the Liupanshui Coalfield, Guizhou, Southwestern China: Geochemical evidence for terrigenous input. *Ore Geol. Rev.* **2019**, *115*, 103190. [\[CrossRef\]](#)
- Dai, S.; Zhou, P.; Zhang, M.; Wang, X.; Wang, J.; Song, X.; Jiang, Y.; Luo, Y.; Song, Z.; Yang, Z.; et al. A new type of Nb(Ta)-Zr(Hf)-REE-Ga polymetallic deposit in the late Permian coal-bearing strata, eastern Yunnan, Southwestern China: Possible economic significance and genetic implications. *Int. J. Coal Geol.* **2010**, *83*, 55–63. [\[CrossRef\]](#)
- Wei, Y.; He, W.; Qin, G.; Fan, M.; Cao, D. Lithium enrichment in the No. 21 coal of the Hebi No. 6 Mine, Anhe Coalfield, Henan Province, China. *Minerals* **2020**, *10*, 521. [\[CrossRef\]](#)
- Zhou, M.; Zhao, L.; Wang, X.; Nechaev, V.P.; French, D.; Spiro, B.F.; Graham, I.T.; Hower, J.C.; Dai, S. Mineralogy and geochemistry of the Late Triassic coal from the Caotang mine, northeastern Sichuan Basin, China, with emphasis on the enrichment of the critical element lithium. *Ore Geol. Rev.* **2021**, *139*, 104582. [\[CrossRef\]](#)
- McLennan, S.M. Rare earth elements in sedimentary rocks: Influence of provenance and sedimentary processes. In *Geochemistry and Mineralogy of Rare Earth Elements*; Lipin, B.R., McKay, G.A., Eds.; De Gruyter: Berlin, Germany, 1989; pp. 169–200.
- Yudovich, Y.E.; Ketris, M.P. Arsenic in coal: A review. *Int. J. Coal Geol.* **2005**, *61*, 141–196. [\[CrossRef\]](#)
- Haskin, L.; Gehl, M.A. The rare earth distribution in sediments. *J. Geophys. Res.* **1962**, *67*, 2537–2541. [\[CrossRef\]](#)
- Frey, F.A.; Haskin, L.A. Rare earths in oceanic basalts. *J. Geophys. Res.* **1964**, *69*, 775–780. [\[CrossRef\]](#)
- Haskin, L.; Gehl, M.A. The rare earth elements contents of standard rocks G-1 and W-1 and their comparison with other rare earth distribution patterns. *J. Geophys. Res.* **1963**, *68*, 2037–2043. [\[CrossRef\]](#)
- Ren, D.; Zhao, F.; Dai, S.; Zhang, J.; Luo, K. *Geochemistry of Trace Elements in Coal*; Science Press: Beijing, China, 2006; 556p. (In Chinese with English abstract)
- Turekian, K.K.; Wedepohl, K.H. Distribution of the elements in some major units of the earth's crust. *Geol. Soc. Am. Bull.* **1961**, *72*, 175–192. [\[CrossRef\]](#)
- Vinogradov, A.P. Average contents of chemical elements in the principal types of igneous rocks of the earth's crust. *Geokhimiya* **1962**, *7*, 555–571. (in Russian); Translation in *Geochemistry* **1962**, *7*, 641–664.
- Şengör, A.M.C.; Yılmaz, Y. Tethyan evolution of Turkey: A plate tectonic approach. *Tectonophysics* **1981**, *75*, 181–241. [\[CrossRef\]](#)
- Robertson, A.H.F.; Dixon, J.E. Introduction: Aspects of the geological evolution of the Eastern Mediterranean. *Geol. Soc. Lond. Spec. Publ.* **1984**, *17*, 1–74. [\[CrossRef\]](#)
- Yılmaz, Y. New evidence and model on the evolution of the southeast Anatolian orogen. *Geol. Soc. Am. Bull.* **1993**, *105*, 251–271. [\[CrossRef\]](#)
- Yılmaz, Y.; Genç, Ş.C.; Yılmaz, A. Geological evolution of the eastern Pontides. *Tectonophysics* **1988**, *148*, 195–233.
- Yılmaz, Y.; Genç, Ş.C.; Gürer, O.F.; Bozcu, M.; Yılmaz, K.; Karacık, Z.; Altunkaynak, Ş.; Elmas, A. When did the western Anatolian grabens begin to develop? *Geol. J.* **1993**, *28*, 27–38. [\[CrossRef\]](#)
- Elmas, A.; Yılmaz, Y. The Late Miocene–Pliocene evolution of the central Anatolian basins: Evidence from the Tuzgölü Basin. *Sediment. Geol.* **2003**, *160*, 67–83.
- Robertson, A.H.F. Mesozoic–Tertiary Tectonic Evolution of the Easternmost Mediterranean area: Integration of Marine and Land Evidence. In *Proceedings of the Ocean Drilling Program, Scientific Results*; Robertson, A.H.F., Emeis, K.-C., Richter, C., Camerlenghi, A., Eds.; Ocean Drilling Program: College Station, TX, USA, 1998; Volume 160, pp. 723–782.
- Robertson, A.H.F. Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region. *Lithos* **2002**, *65*, 1–67. [\[CrossRef\]](#)
- Robertson, A.H.F.; Ustaömer, T.; Parlak, O. Overview of the Palaeozoic and Mesozoic geology of the Eastern Mediterranean region. *Geol. Soc. Lond. Spec. Publ.* **2012**, *372*, 1–55. [\[CrossRef\]](#)
- Yılmaz, Y. Geology of the eastern Pontides. *Geol. Bull. Turkey* **1984**, *27*, 1–20.
- Yılmaz, Y.; Genç, Ş.C.; Yılmaz, A. Petrology and geochemistry of the eastern Pontide volcanic rocks. *Tectonophysics* **1987**, *139*, 195–233.
- Rigo de Righi, M.; Cortesini, A. Gravity tectonics in foothills structure belt of southeast Turkey. *AAPG Bull.* **1964**, *48*, 1911–1937. [\[CrossRef\]](#)

29. Yılmaz, Y.; Yiğitbaş, E.; Çemen, İ. Tectonics of the Southeast Anatolian Orogenic Belt. In *Compressional Tectonics: Plate Convergence to Mountain Building*; Catlos, E.J., Çemen, İ., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2023; pp. 203–222.
30. Baydar, O. Berit-Kandil Dağları (Kahramanmaraş) ve civarının jeolojisi. Ph.D. Thesis, İstanbul Üniversitesi, Fen Bilimleri Enstitüsü, İstanbul, Turkey, 1989. Unpublished Ph.D. Thesis. (In Turkish)
31. Yusufoglu, H.; Bedi, Y.; Beyazpirinç, M.; Özkan, M.K.; Usta, D.; Yıldız, H. Doğu Toroslar'ın jeodinamik evrimi (Afşin-Elbistan-Göksun-Sarız dolayları). Maden Tetkik ve Arama Genel Müdürlüğü Rapor No: 1150, Ankara, Turkey, 2005. Unpublished Report. (In Turkish)
32. Cicioğlu, E. Çöllolar Kışlaköy (Afşin-Elbistan) linyitlerinin jeokimyasal özelliklerinin incelenmesi. Ph.D. Thesis, Hacettepe Üniversitesi, Ankara, Turkey, 2001. (In Turkish)
33. Robertson, A.H.F.; Parlak, O.; Ustaömer, T. Overview of the Palaeozoic-Neogene evolution of Neotethys in the eastern Mediterranean region (southern Turkey, Cyprus, Syria). *Pet. Geosci.* **2012**, *18*, 381–404. [\[CrossRef\]](#)
34. Yılmaz, A.; Bedi, Y.; Uysal, Ş.; Aydın, N. 1:100,000 Scaled Geologic Maps of Turkey, Elbistan-I23 Quadrangle; No: 50; MTA, Department of Geological Research: Ankara, Turkey, 1997.
35. GB/T 14506.30-2010; Methods for Chemical Analysis of Silicate Rocks—Part 30: Determination of 44 Elements. Standardization Administration of China: Beijing, China, 2010.
36. GBW07103 (GSR-1); Grey Medium-Grained Biotite Granite. National Institute of Metrology: Beijing, China, 2016.
37. GBW07105 (GSR-3); Alkali-Olivine Basalt. National Institute of Metrology: Beijing, China, 2016.
38. Taylor, S.R.; McLennan, S.M. *The Continental Crust: Its Composition and Evolution*; Blackwell: Oxford, UK, 1985; p. 312.
39. Yuan, Y.; Liu, S.; Wu, M.; Zhong, M.; Shahid, M.Z.; Liu, Y. Effects of topography and soil properties on the distribution and fractionation of REEs in topsoil: A case study in Sichuan Basin, China. *Sci. Total Environ.* **2021**, *791*, 148404. [\[CrossRef\]](#)
40. Dai, S.; Luo, Y.; Seredin, V.V.; Ward, C.R.; Hower, J.C.; Zhao, L.; Liu, S.; Tian, H.; Zou, J. Revisiting the Late Permian Coal from the Huayingshan, Sichuan, Southwestern China: Enrichment and Occurrence Modes of Minerals and Trace Elements. *Int. J. Coal Geol.* **2014**, *122*, 110–128. [\[CrossRef\]](#)
41. Wen, L.; Huang, W.; Zhang, Y.; Jiu, B. Geochemical characteristics of rare earth elements in late Palaeozoic coals from North China. *Front. Earth Sci.* **2024**, *12*, 1374780. [\[CrossRef\]](#)
42. Vassilev, S.V.; Vassileva, C.G. Methods for Characterization of Composition of Fly Ashes from Coal-Fired Power Stations: A Review. *Fuel* **2005**, *84*, 389–408.
43. Adriano, D.C.; Page, A.L.; Elsewii, A.A.; Chang, A.C.; Straughan, I. Utilization and Disposal of Fly Ash and Other Coal Residues in Terrestrial Ecosystems: A Review. *J. Environ. Qual.* **1980**, *9*, 333–344. [\[CrossRef\]](#)
44. Vassilev, S.V.; Menendez, R.; Alvarez, D.; Diaz-Somoano, M. Phase-Mineral and Chemical Composition of Coal Fly Ashes as a Basis for Their Multicomponent Utilization. 1. Characterization of Feed Coals and Fly Ashes. *Fuel* **2003**, *82*, 1793–1811. [\[CrossRef\]](#)
45. Vassilev, S.V. Phase Mineralogy Studies of Solid Waste Products from Coal Burning at Some Bulgarian Thermoelectric Power Plants. *Fuel* **1992**, *71*, 625–633. [\[CrossRef\]](#)
46. Querol, X.; Juan, R.; López-Soler, A.; Plana, F.; Alastuey, A.; Zhuang, X. Coal Combustion and Gasification Residues: Characteristics and Use. In *Minerals and Their Use in Geopolymer Technology*; Elsevier: Amsterdam, The Netherlands, 2001; pp. 93–119.
47. Finkelman, R.B. Trace and minor elements in coal. In *Organic Geochemistry*; Engel, M.H., Macko, S.A., Eds.; Plenum Press: New York, NY, USA, 1993; pp. 593–607.
48. Vassilev, S.V.; Kitanob, K.; Takedab, S.; Tsurueb, T. Influence of mineral and chemical composition of coal ashes on their fusibility. *Fuel Process. Technol.* **1995**, *45*, 27–51. [\[CrossRef\]](#)
49. Lu, Y.; Wang, Y.; Zhao, Y.; Wei, Z.; Li, Y.; Hao, W.; Zhang, Y. The Characteristics of Mineralogy, Morphology and Sintering during Co-Combustion of Zhundong Coal and Oil Shale. *RSC Adv.* **2017**, *7*, 51036–51045. [\[CrossRef\]](#)
50. Cicioğlu Sütçü, E.; Karayığit, A.İ. Mineral matter, major and trace element content of the Afşin-Elbistan coals, Kahramanmaraş, Turkey. *Int. J. Coal Geol.* **2015**, *144–145*, 111–129. [\[CrossRef\]](#)
51. Budakoğlu, M.; Abdelnasser, A.; Karaman, M.; Kumral, M. The rare earth element geochemistry on surface sediments, shallow cores and lithological units of Lake Acıgöl basin, Denizli, Turkey. *J. Asian Earth Sci.* **2015**, *111*, 632–662. [\[CrossRef\]](#)
52. Sun, S.S.; McDonough, W.F. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In *Magmatism in the Ocean Basins*; Saunders, A.D., Norry, M.J., Eds.; Geological Society: London, UK, 1989; Volume 42, pp. 313–345.
53. Wang, L.; Liang, T. Anomalous abundance and redistribution patterns of rare earth elements in soils of a mining area in Inner Mongolia, China. *Environ. Sci. Pollut. Res.* **2016**, *23*, 11330–11338. [\[CrossRef\]](#)
54. de Sá Paye, H.; de Mello, J.W.; de Magalhães Mascarenhas, G.R.L.; Gasparon, M. Distribution and fractionation of the rare earth elements in Brazilian soils. *J. Geochem. Explor.* **2016**, *161*, 27–41. [\[CrossRef\]](#)
55. Yudovich, Y.; Ketris, M.P. Estimations of Clarkes for Carbonaceous Biolithes: World Averages for Trace Element Contents in Black Shales and Coals. *Int. J. Coal Geol.* **2009**, *78*, 135–148. [\[CrossRef\]](#)

56. Demir, I.; Ruch, R.; Damberger, H.; Harvey, R.; Steele, J.; Ho, K. Environmentally Critical Elements in Channel and Cleaned Samples of Illinois Coals. *Fuel* **1998**, *77*, 95–107. [[CrossRef](#)]
57. Dai, S.; Seredin, V.V.; Ward, C.R.; Jiang, J.; Hower, J.C.; Song, X.; Jiang, Y.; Wang, X.; Gornostaeva, T.; Li, X.; et al. Composition and Modes of Occurrence of Minerals and Elements in Coal Combustion Products Derived from High-Ge Coals. *Int. J. Coal Geol.* **2014**, *121*, 79–97. [[CrossRef](#)]
58. Seredin, V.V.; Dai, S. Coal Deposits as Potential Alternative Sources for Lanthanides and Yttrium. *Int. J. Coal Geol.* **2012**, *94*, 67–93. [[CrossRef](#)]
59. Dai, S.; Li, T.; Jiang, Y.; Ward, C.R.; Hower, J.C.; Sun, J.; Liu, J.; Song, H.; Wei, J.; Li, Q.; et al. Mineralogical and geochemical compositions of the Pennsylvanian coal in the Hailiushu Mine, Daqingshan Coalfield, Inner Mongolia, China: Implications of sediment-source region and acid hydrothermal solutions. *Int. J. Coal Geol.* **2015**, *137*, 92–110. [[CrossRef](#)]
60. Dai, S.; Bechtel, A.; Eble, C.F.; Flores, R.M.; French, D.; Graham, I.T.; Hood, M.M.; Hower, J.C.; Korasidis, V.A.; Moore, T.A.; et al. Recognition of Peat Depositional Environments in Coal: A Review. *Int. J. Coal Geol.* **2020**, *219*, 103383. [[CrossRef](#)]
61. Fu, X.; Liu, X.; Wu, Q.; Xiao, B.; Fan, C. Influence of magma intrusion on coal geochemical characteristics: A case study of Tiefsa Daxing coal mine. *Sci. Rep.* **2024**, *14*, 7396. [[CrossRef](#)]
62. Wang, W.; Qin, Y.; Song, D.; Sang, S.; Jiang, B.; Zhu, Y.; Fu, X. Element Geochemistry and Cleaning Potential of the No.11 Coal Seam from Antabao Mining District. *Sci. China Ser. D Earth Sci.* **2005**, *48*, 2142–2154. [[CrossRef](#)]
63. Laveuf, C.; Cornu, S. A review on the potentiality of rare earth elements to trace pedogenetic processes. *Geoderma* **2009**, *154*, 1–12. [[CrossRef](#)]
64. Vassilev, S.V.; Vassileva, C.G. A New Approach for the Classification of Coal Fly Ashes Based on Their Origin, Composition, Properties, and Behavior. *Fuel* **2007**, *86*, 1490–1512. [[CrossRef](#)]

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