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Rare earth elements of fly ash from Wyoming's Powder River Basin coal¹

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Abstract

The advancement and increasing interests in green energy production and environmental protection technologies have spurred the demand for rare earth elements. On the other hand, the U.S. has to rely 100% on import of these materials as the industry was crashed because of the environmental issues associated with mining and processing, and more importantly lack competitiveness. As rare earth elements have many applications in defense and national security sectors, some of the elements were listed as strategic materials or critical materials because of the uncertainties in supply and prices. Therefore, it has become imperative in searching for alternative resources for supplying rare earth elements including unconventional resources. With the strong incentive, coal fly ash is identified as one of the candidates among them. In this study, we present rare earth element data for the 42 ash samples (all derived from Powder River Basin coal) that we collected from seven states (UT, WY, IO, WI, ND, CO, and MI) representing 158 million tons of fly ash. The results indicate scattered distributions of rare earth elements with concentration ranging from 156 to 590 ppm although all the ash samples originated from the same coal basin (Powder River Basin). The rare earth element resource in these ashes is estimated between 74000 to 106000 tons. The ash samples were also characterized by Elemental analysis, XRD, SEM-EDS, and BET surface area. The characterizations of the ashes were discussed as they might have implications in the subsequent rare earth element extraction processes. In summary, fly ash may represent a potential resource for rare earth element production.

Keywords: Rare earth elements; coal fly ash; XRD; SEM-EDS; BET surface area; critical materials

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1. Introduction

Rare earth elements are a group of 17 chemical elements in the periodic table, including scandium, yttrium and 15 lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium). In this paper, we narrowly define REEs to represent 14 naturally occurring lanthanide elements and REY to represent REEs plus yttrium. These elements are metals with nearly identical chemical properties and comprising approximately 17% of all naturally occurring elements.¹⁻⁴ Historically, total rare earth oxides (TREOs) include 14 naturally occurring rare earth elements (REEs) and yttrium in the mining industry to represent the total rare earth elements concentration in the samples although the mineral occurrence may not be in oxide forms.⁵ Rare earth elements have been subdivided into two groups, i.e., light rare earth elements (LREEs) and heavy rare earth elements (HREEs), according to their atomic weight. LREEs include elements from lanthanum (atomic weight 138.91) through europium (atomic weight 151.96) while HREEs include elements from gadolinium (atomic weight 157.25) through lutetium (atomic weight 174.97) with yttrium.^{5,6} LREEs-containing minerals include bastnasite, monazite, allanite, loparite, ancylite, parasite, lanthanite, chevinite, cerite, stillwellite, britholite, fluocerite, and cerianite while HREEs-containing minerals are found in gadolinite, xenotime, samarskite, euxenite, fergusonite, yttrotantalite, yttrotungstite and yttrialite.⁶ However, bastnasite, monazite, xenotime, and rare-earth ion-adsorption clays are the ores that dominate the production of rare earth elements in the world.⁴⁻⁷ The corresponding salts of these minerals are bastnasite, carbonate (e.g. Mountain Pass Mine and Bayan Obo); monazite, phosphate; and xenotime, yttrium-dominated phosphate.⁵

The first industrial application of rare earth elements can be dated back to the late 19th century.³ Rare earth elements play an important role in many areas ranging from household products to materials used in high technologies because of their unique properties in magnetic, luminescent, and chemical aspects.⁸ Catalysts, ceramics and glass, metallurgical use and alloys manufacturing, and polishing are the major industries that consume thousands of tons of rare earth elements.⁹ Applications of rare earth elements in clean energy technologies and high-technology products such as permanent magnet, lasers, healthcare devices, catalysts, rechargeable batteries, and many others.^{4,10-12} Development of high technologies have led to significant increases in the annual growth of rare earth element consumption at rates of 3.7%-8.6%, although they vary with different scenarios.¹³ However, the production of rare earth elements remains limited in a few countries, as indicated in Fig. 1, because of resources constraint, technical difficulties, regulatory hurdles, and capital costs. As a result, many countries including the U.S. are continuously addressing the dependency risks on rare earth elements and have listed rare earth elements as the “critical materials”, especially dysprosium (Dy), neodymium (Nd), terbium (Tb), europium (Eu) and yttrium (Y) in response to the

uncertainties in supply and prices. These elements are used in green energy technologies including permanent magnets for high-efficiency motors and advanced lighting systems that have high demand and limited substitutes.^{14,15} In addition, the supply of rare earth elements in the U.S. solely relies on import as the domestic production of rare earth elements was ceased. Figs. 1 and 2 show the world reserves and production of rare earth elements, respectively. China, Brazil, and Russia hold 70% of the world's rare earth element reserves. China alone has been the dominating rare earth element producer since the late 1990s, accounting for over 79% rare earth element production on a global scale.⁹

Unconventional rare earth element-containing resources, including produced water, acid mine drainage, and coal/coal-by-products contain a significant amount of rare earth elements. These resources have attracted increasing attentions because of the surge of the demands, volatile prices, and uncertainties in supply of the conventional rare earth elements.^{14,15} These are considered as potential rare earth element resources for exploitation. Developing a sustainable domestic supply with environmentally benign and economically competitive technologies is important for reducing the dependence on others for these critical materials and ameliorate the risk associated with them.

Coal and coal by-products such as coal fly ash have been known to contain rare earth elements.¹⁶ NETL has estimated that potentially over 10 million tons of rare earth elements can be recovered from the currently known coal reserves in the 9 coal-producing states (WY, CO, UT, NM, AZ, PA, WV, KY & VA).¹⁷ It was estimated that the average total rare earth element concentration in the U.S. coal is ~65.5 ppm and 485 ppm in ash on a dry basis,¹⁸ compared to 68.5 ppm of coal and 404 ppm in coal ash in a global scale.^{8,19} Others reported that the average concentration of total rare earth elements in some coalfield could be as high as 392 ppm and over 1000 ppm even several thousand in some discrete samples.¹⁹⁻²⁷ The enrichment of rare earth elements in coal has implications that coal has economic values for these metals as by-products during coal cleaning or combustion residues. Coal ash also referred to as coal combustion residuals is the by-product of coal combustion. It includes fly ash, bottom ash, boiler slag, and flue gas desulfurization materials. It is believed that fly ash carries most of the rare earth elements from coal. The reported rare earth element concentration in ash in an oxide basis is as high as 1.85%.²⁶ The concentration is even higher than some of the rare earth element ores. Ores containing 1%–2% rare earth elements are considered good, suggesting that coal ash with enriched rare earth elements could have a great economic potential.⁵ On the other hand, coal ash is one of the largest industrial wastes. American Coal Ash Association reported that the U.S. alone produced 107.4 million tons in 2016 with about 1.5 billion tons in stockpiles,^{28,29} while worldwide annual production was about 780 million metric tons.³⁰ Increasing interests have been exerted in the recent decade on coal fly ash as it could potentially serve as one of the alternative resources for rare earth elements. Understanding the patterns and distributions of rare earth elements in fly ash become important for the technological and economic evaluation of its potential. In this study, we have analyzed 42 coal fly ash samples collected from power plants, landfills, and ponds

from 7 states including Utah, Wyoming, Iowa, Wisconsin, North Dakota, Colorado, and Michigan. These samples represent a total of 158 million tons of coal fly ash resources. The fly ash was characterized and the composition of rare earth elements was investigated to show its potential as an alternative rare earth element resource. The correlation between rare earth elements and minerals and its implication in beneficiation were also discussed. The aims of this study are to provide information on the properties of the coal fly ash samples and estimate rare earth element resources held in the ash.

2. Materials and methods

2.1 Coal ash samples

42 coal fly ash samples were collected from 7 states (UT, WY, IO, WI, ND, CO, and MI) that were generated from 19 power plants (Fig. 3). The samples were collected from the stations, landfill sites, and/or ponds. The coal ash was sealed in a 5-gallon bucket and shipped to the lab by couriers. The sampling, analytical, and procedural techniques were based on ASTM standards, D5759-12 to obtain coal ash from power plants, ASTM D346 for sampling coal ash from lots of less than 100 t, and ASTM D346 & D2013 for crushing dividing and meshing procedure of collected coal as samples.

2.2 Ash characterizations

Elemental analysis (CHNS), Brunauer-Emmett-Teller (BET) surface areas, X-ray powder diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) were conducted to characterize the ash samples. Samples were dried to constant mass in a vacuum oven at 105 °C. A vario MACRO cube elemental analyzer (vario MACRO cube, Elementar) was used for elemental analysis under vario MACRO cube CHNS mode. The coal 50 method was adopted to measure the elements including C, H, N, and S in the coal fly ash samples. BET surface areas of coal fly ash samples were evaluated by using nitrogen adsorption isotherms obtained at -196 °C with a Quantachrome Autosorb-iQ instrument. Samples were degassed at 150 °C for 8 hours under vacuum before analysis. XRD analysis was conducted with a Powder X-ray Diffractometer manufactured by Rigaku with Cu K α radiation. The working voltage and current of the X-ray tube were fixed at 40 kV and 40 mA, respectively. A thin layer of the sample was mounted evenly onto a zero background quartz plate, followed by running with a scan range of 2 θ between 10 °–90 ° and at a scan rate of 4 (°)/min with a chopper increment of 0.02°. The XRD data were analyzed with Jade 6.5 by Material Data, Inc. (MDI). Peak profiles of individual reflections were determined by a nonlinear least-squares fit of the Cu K α corrected data. Morphology was studied using a scanning electron microscope in HV mode with an accelerating voltage of 20 kV (SEM-EDS, FEI, Quanta FEG MK2; Oxford Instruments America, Model #51-XXM0005).

2.3 Elemental ash analysis by ICP/MS

A Perkin Elmer NexION 300S ICP-MS was used for analyzing the concentration of rare earth

elements in the samples. The instrument was operated under standard mode and all analyses were completed using external standards and Rhenium at a concentration of 50 ppb was used as the internal standard. The ash was digested according to Bank et al.³¹ Briefly, the ash was mixed with LiBO₂ (lithium metaborate) at a ratio of 1:8 by weight. Prior to fusion, samples were mixed by stirring with a platinum rod in a 99.95% platinum crucible. The crucible was heated to 1100 °C for 5 min in a muffle furnace. After fusion, the melt was removed from the oven to cool to homogeneous glass. The glass was digested in 5% HNO₃ (trace metal) with low heat and stirring for ten minutes. The acid digestion was repeated for 4 times to ensure that the sample glass was completely digested and dissolved. The collected liquid sample was diluted to the scale of 100 mL. The accuracy of the fusion method was assessed using the National Institute of Standards and Technology (NIST) standard reference material (SRM) for coal fly ash, SRM 1633c.

3. Results and discussion

3.1 Rare earth element composition, abundance, and distribution

Table 1 shows the REY concentration of all the 42 ash samples. The total concentration of REY ranged from 156.0 ppm to 590.3 ppm in the dried mass basis. Among the 42 samples, 3 are below 200 ppm, 4 between 200 and 300 ppm, 14 between 300 and 400 ppm, 14 between 400 and 500 ppm, and 9 between 500 and 600 ppm. The mean value of the REY of all 42 samples is 399.5 ppm which is comparable to the world average (404 ppm) but significantly lower than the U.S. average of 485 ppm.^{8,19} Ce is the most abundant element in all the ashes, followed by Nd, La, and Y. These four elements consist of the majority of the total rare earth elements, ranging from 76.0% to 84.6%. Despite the fact that all the ashes originated from Powder River basin coal, the scattered distribution of the total REY could be attributed to a number of reasons, i.e., the origin of coal (different coal seams), coal preparation and combustion, and possibly sampling schemes.^{27,32} However, little is known and further investigation is needed to unveil the underlying causes.

The more valuable HREE comprises 20.3%–28.8% of the total REEs in all the samples with an average of 24.1% (Fig. 4). The fraction of critical rare earth elements ranges from 35.2% to 39.6% with a mean value of 37.0%. The reported values are well scattered from as low as 16.8% to as high as 63.2%.^{26,27,33} Taggart et al. reported shares of critical rare earth elements ranging from 28.5% to 41.0% with a median of 36.5%, which is quite comparable to this study.²⁷

The 42 ash samples had been collected from 19 power plants which could give us an insight over the concentration of rare earth elements. The rare earth element concentration could vary from the same power plant with respect to sampling sites (power plant, landfills, and ponds), sampling time, and even artificial effects from sampling schemes. For example, PP2-1-PP

and PP2-2-LF were collected from the same power plant but different sites, i.e., power plant and landfill. The mean value of the two samples is 465 ppm with a standard deviation of 53 which is over 11% of the mean value. Sampling time could also have great impacts. In the DJ station, one ash sample was (DJ1-PP) collected in November 2015 and the other two (DJ2-PP and DJ3-PP) were collected in February 2017. The concentration of the two 2017 samples is 347 ± 9 ppm, indicating that the sampling practice is consistent. However, when compared with the 2015 sample (460 ppm), the difference is significant. The difference could be attributed to several causes including the alteration of power plant operation, coal quality, etc. Although differences derived from sampling schemes have been observed, many data pairs exhibit great reproducibility (Table 1).

3.2 Elemental analysis and correlation of REY to minerals

Elemental analyses were conducted with the collected ashes. Table 2 shows examples of the elemental composition of the ashes. The elemental composition of the ash varies, depending on the origin of the coal, the coal preparation, and the combustion processes. The residual carbon varies from a fraction of a percent to a couple of percent. The residual coal carbon in fly ash was found to have the capacity of absorbing metal species such as mercury.³⁴ The size of the residual carbon could significantly affect the surface area which in turn has impacts on the adsorption/desorption capability.³⁵ However, absorption of rare earth elements has not been reported. The concentration of sulfur could comprise as high as several percent of the total ash mass. This should be taken into consideration as it can pose an environmental threat.

Mineral composition of the ash samples was also analyzed. The main components include Ca, Si, Al, Fe, Mg, Ti, Na, K, and Ba. The correlation of mineral concentration and REY is depicted in Fig. 5. The ash samples in the figure were sorted in ascending order with respect to the REY concentrations. The results have shown that the REY concentration is positively correlated to the mineral concentration, suggesting the form of minerals might have impacts on the enrichment/detainment of rare earth elements which implies an alternative way of rare earth element beneficiation from coal fly ash.

3.3 Brunauer-Emmett-Teller (BET) surface area

The examples of surface areas of samples are shown in Table 3. The coal fly ash samples have a wide range of BET surface areas ($0.9\text{--}19.3\text{ m}^2/\text{g}$) suggesting that the characteristics of coal fly ashes are significantly impacted by the ways of coal preparation and combustion. Others reported surface area of fly ash for up to $30\text{ m}^2/\text{g}$.³⁶ Studies found that rare earth element concentration is negatively correlated to the particle size of fly ash, i.e., finer particles have higher rare earth elements content.³⁷ This suggests that rare earth elements may deposit on the surface of the fly ash particles. Therefore, surface areas of ash could be an important parameter for the recovery of rare earth elements as increases in surface areas

could increase the chance of collision and exposure for attacks, and hence increase the rate and yield of extraction.

3.4 SEM-EDS analysis of coal ash

Amorphous structure and cenospheres with intergrown minerals are shown in Fig. 6(a). The morphology and particles of fly ash are associated with the combustion temperature in the boiler and the rate of cooling.³⁸ The operating temperature in a pulverized coal-fired boiler is generally over 1400 °C to render the minerals to fluid forms. The rapid cooling in the post-combustion zone induces the formation of spherical and amorphous particles. The cenospheres are cryptocrystalline aluminosilicates which comprise aluminum, silicon, and oxygen, as EDS images have suggested (Fig. 6(b, j)). Other dominant elements including Ca, Fe, and Mg (Fig. 6(c, e, g)) were distributed in a more random pattern. The analysis also confirmed that Ce, Nd, La, and Y are abundant and well scattered among the ash particles, although a study using SHRIMP-RG ion microprobe to investigate the distribution of rare earth elements in fly ash concluded that aluminosilicates should be targeted for rare earth element recovery.³⁹ Another study showed that rare earth elements are enriched in non-magnetic fractions of the ash samples.³⁷

3.5 XRD analysis of coal fly ashes

Fig. 7 is an example of XRD of the ash (No. 21). The peak profiles of individual reflections were determined by a nonlinear least-squares fit of the Cu K α corrected data. The analysis shows the presence of quartz, periclase, anhydrite, lime, and neodymium-calcium-manganese oxide. The data confirm the presence of major elements that were detected in SEM-EDS studies (Section 3.4). It also shows that one of the major rare earth elements, Nd, is associated with Ca-manganese oxide complex.

4. Conclusions

Coal is and will continue to be one of the primary energy sources for fueling the world. It is inextricably to see an increased production of ash in the foreseeable future as the projected growth rate of using coal for power generation is 3.4% annually.¹⁴ Fly ash, where most of the rare earth elements reside, comprises 35.2% of the total 107.4 million tons of coal combustion products in 2016.²⁸ On the other hand, coal fly ash has been known to contain rare earth elements. In this study, we have found that the concentrations of rare earth elements are well scattered given the fact that all the ash samples originated from Powder River Basin. Even in the same power plant, the rare earth element contents could be impacted by spatial (landfill/ponds), temporal (sampling time), and artificial (coal preparation and operation) factors. The concentrations of rare earth elements are found to be positively correlated to the concentrations of minerals in general. The total amount of REY in these ash

samples is estimated between 74000 to 106000 t as TREOs, compared to 16000 t of consumption in the USA in 2016.⁹ In addition, there is also about 1.5 billion tons in stockpiles in the USA, although the share of fly ash and composition of rare earth elements remain in question. However, the data presented herein demonstrate that fly ash contains a great amount of rare earth elements overall. As extraction and separation technologies advanced, there is great potential to recover rare earth elements from fly ash.

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376 **Tables**377 **Table 1** REEs concentrations (ppm or mg/kg ash) in 42 ash samples on a dried mass basis

Abbrev.	No.	Ce	Dy	Er	Eu	Gd	Ho	La	Lu	Nd	Pr	Sm	Tb	Tm	Y	Yb	Total
BH1-PP ^a	1	44	5	3	4	5	1	24	1	26	6	8	1	1	24	3	156
BH2-PP	2	45	5	3	4	5	1	25	0	28	6	8	1	0	25	3	160
CH-PP	3	167	11	7	3	14	2	89	1	100	23	15	2	1	61	7	503
DFS1-PP	4	149	14	8	5	22	3	75	1	100	23	22	2	1	70	7	503
DFS2-LF ^b	5	152	12	8	7	17	5	78	3	92	20	18	4	3	64	7	492
DFS3-LF	6	142	11	6	5	14	3	73	1	87	16	16	2	1	58	5	441
DJ1-PP	7	143	12	7	5	16	2	76	1	92	17	16	2	1	63	6	460
DJ2-PP	8	115	9	6	4	11	2	59	1	66	13	11	2	1	47	6	354
DJ3-PP	9	110	8	5	3	11	2	59	1	64	12	11	2	1	48	4	341
ER1-PP	10	144	11	7	4	15	3	73	1	88	16	15	3	1	65	6	453
ER2-PP	11	149	10	6	6	15	2	80	1	90	16	16	2	1	56	5	455
H1-PP	12	120	9	6	3	11	2	65	1	71	14	11	2	1	53	6	374
H2-LF	13	107	8	5	3	10	2	57	1	63	13	9	2	1	45	5	331
HCD1-PP	14	114	8	6	3	10	2	62	1	67	13	10	2	1	45	5	350
HCD2-LF	15	116	8	6	3	10	2	64	1	69	14	10	2	1	46	5	358
JB1-PP	16	50	5	3	3	6	1	28	1	29	7	7	1	1	24	3	167
JB2-PP	17	98	7	5	4	9	2	52	1	58	12	10	2	1	38	4	301
L5-PP	18	154	11	6	4	15	2	89	1	97	18	14	2	1	72	5	491
LO1-PP	19	81	7	5	5	8	2	41	1	47	10	11	2	1	44	5	269
LO2-PP	20	97	9	6	6	10	2	50	1	56	11	13	2	1	57	6	327
LR1-PP	21	159	12	7	4	15	2	86	1	98	22	15	2	1	68	7	501
LR2-PP	22	170	15	9	6	22	3	89	1	109	25	24	3	1	76	8	561
LR3-PP	23	143	11	6	5	15	3	73	1	89	17	16	2	1	59	5	445
LR4-PP	24	135	10	6	5	14	2	71	1	83	16	15	2	1	54	5	420
N1-PD ^c	25	111	7	5	3	10	2	62	1	67	13	11	2	1	44	4	343
N2-PP	26	81	6	4	3	8	1	41	1	47	10	9	1	1	34	4	252
N3-PP	27	153	12	7	5	16	3	74	1	97	18	17	3	1	65	7	481
N4-PD	28	163	13	8	6	17	3	79	1	102	19	17	3	1	69	7	508
O6-PP	29	184	13	8	5	18	3	104	1	116	22	18	2	1	88	7	590
OC1-PP	30	140	10	6	5	14	2	75	1	84	15	16	2	1	53	5	428
OC2-PP	31	140	10	6	5	13	3	73	1	82	16	15	3	1	51	6	423
P11-PP	32	123	9	6	6	12	3	61	1	73	14	14	3	1	48	5	382
P12-PP	33	108	8	5	5	10	2	54	1	64	13	12	2	1	41	5	332
PC4-PP	34	133	8	5	3	11	2	78	1	82	14	11	2	1	48	4	403
PP1-PP	35	158	14	9	6	17	5	80	3	95	20	17	4	3	75	8	517
PP2-1-PP	36	158	12	8	7	17	4	84	3	96	21	18	4	3	61	7	503
PP2-2-LF	37	131	11	7	6	15	4	70	3	80	17	15	4	3	56	6	428
WD1-PP	38	162	15	9	5	23	3	84	1	108	25	23	3	1	74	8	544
WD2-PP	39	134	10	6	5	14	2	71	1	83	16	14	2	1	55	5	419
WD3-PP	40	119	9	5	4	12	2	64	1	74	14	13	2	1	49	5	373

WP-1-PP	41	100	8	5	4	11	2	48	1	61	12	11	2	1	42	5	315
WP-2-PP	42	105	9	6	5	11	2	50	1	64	13	12	2	1	44	5	329

^asampled from power plants; ^bsampled from landfills; ^csampled from ponds.

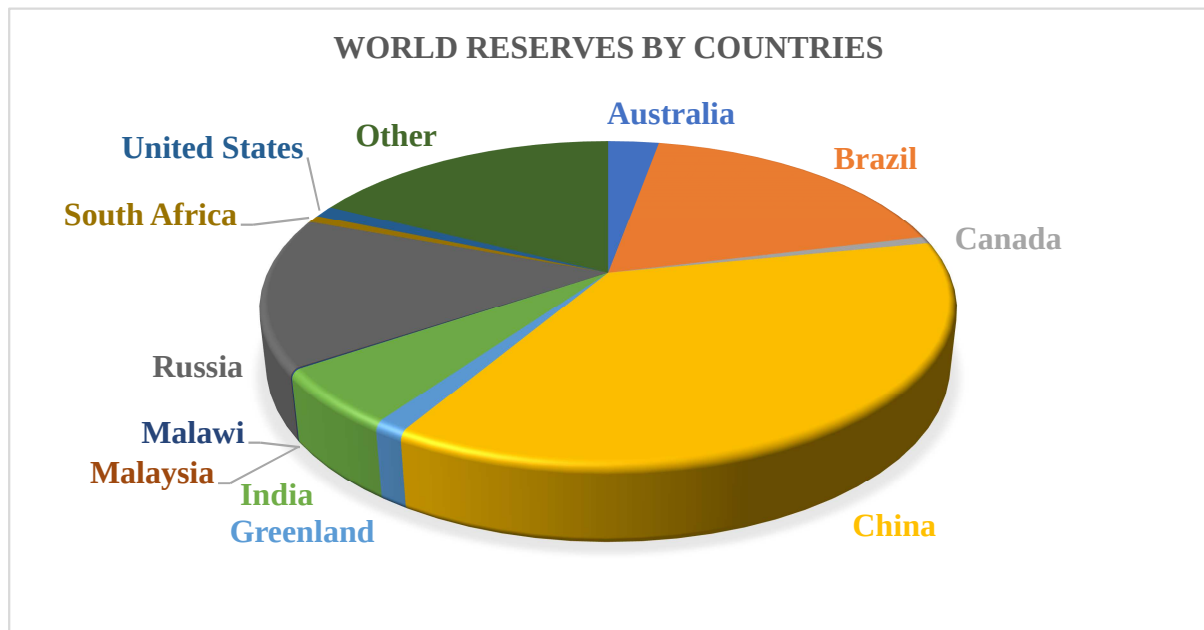
Table 2 Elemental analysis for coal fly ash samples on a dried mass basis (wt%).

Ash ID	C	H	N	S
CH-PP	0.88	0.21	0.03	4.19
DJ1-PP	0.89	0.82	0.06	5.58
DFS1-PP	1.8	0.31	0.03	3.41
LR1-PP	0.26	0.25	0.02	0.91
WD1-PP	0.56	0.24	0.04	3.5

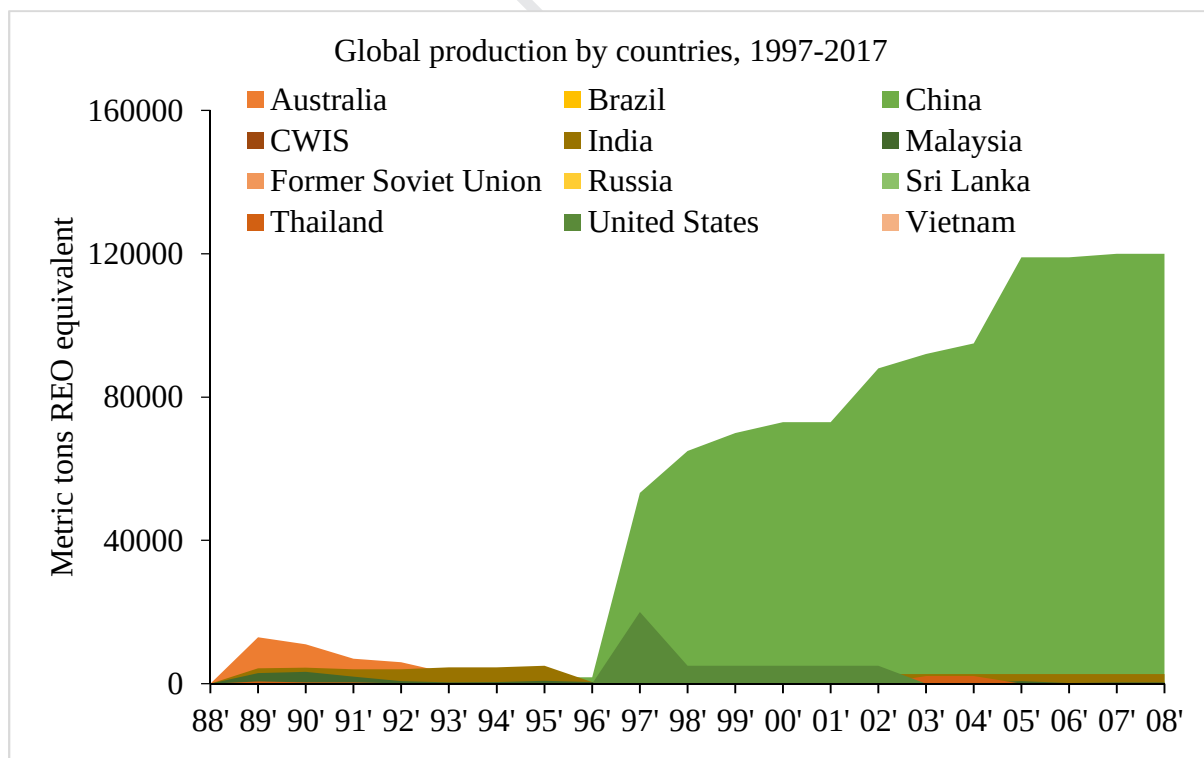
Table 3 Examples of BET surface areas of the coal fly ash samples.

Ash ID	Surface area/m ² /g
CH-PP	1.734
DJ1-PP	13.743
DFS1-PP	5.99
LR1-PP	0.905
WD1-PP	19.32

405 **Figures**



407 **Figure 1** World rare earth element reserves by countries. China accounts for 36.7% of the
 408 world reserves, followed by Brazil, 18.3%, and Russia, 15.0%. These three countries account
 409 for 70% of the world REEs reserves.⁹



412 **Figure 2** Global production of rare earth elements, 1997-2017. CWIS = Commonwealth of
 413 Independence States.⁹

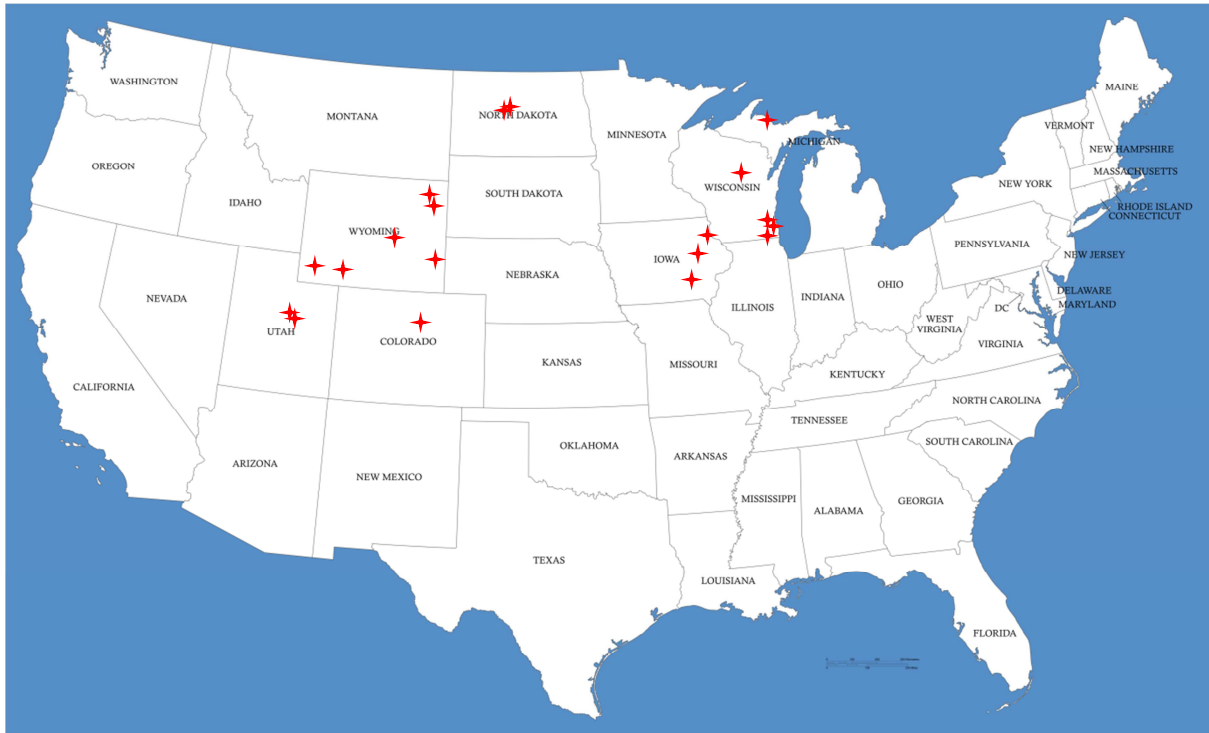


Figure 3 The map of sampling sites of the 42 coal fly ashes. The ashes were collected from 19 power plants (stations, landfill sites, and/or ponds) from 7 states including Utah, Wyoming, Iowa, Wisconsin, North Dakota, Colorado, and Michigan.

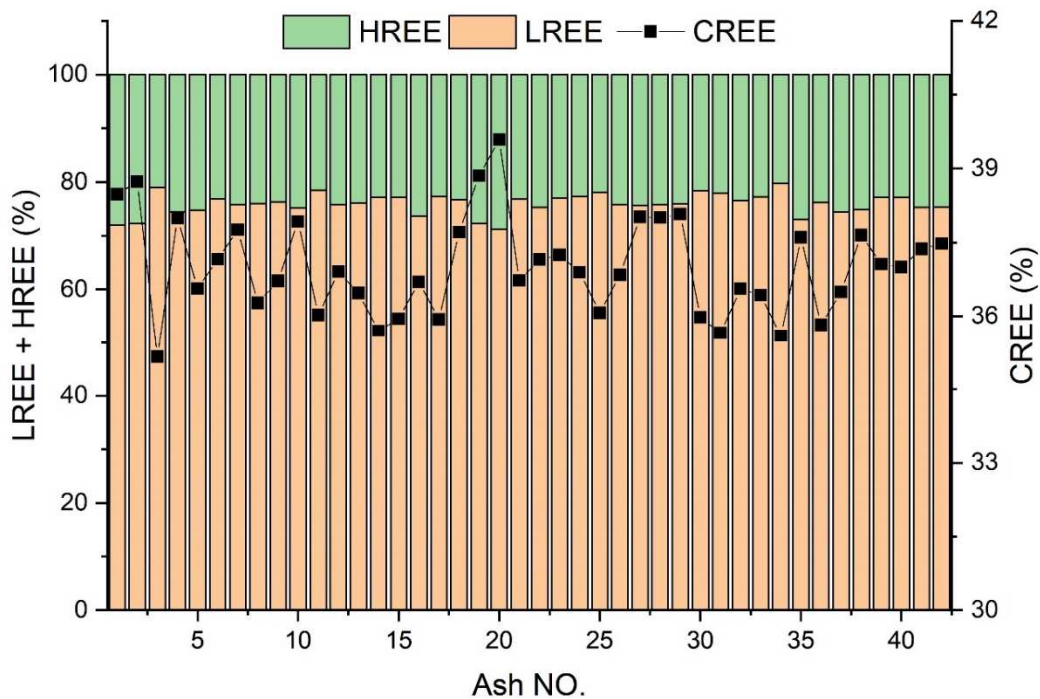


Figure 4 REY distribution in the 42 ash samples. HREE=heavy REEs (La, Ce, Pr, Nd, Sm, and Eu); LREE=light REEs (Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y); CREE=critical REEs (Nd, Eu, Tb, Dy, and Y).

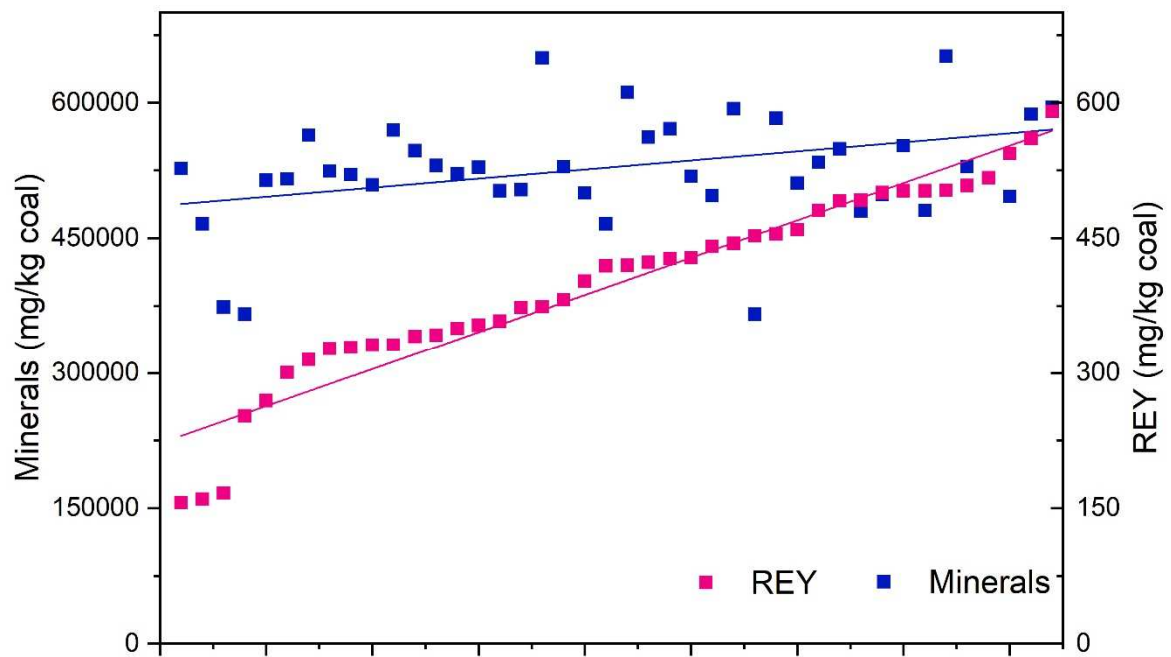
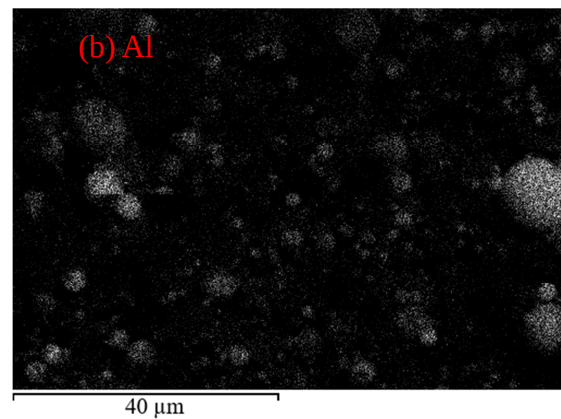
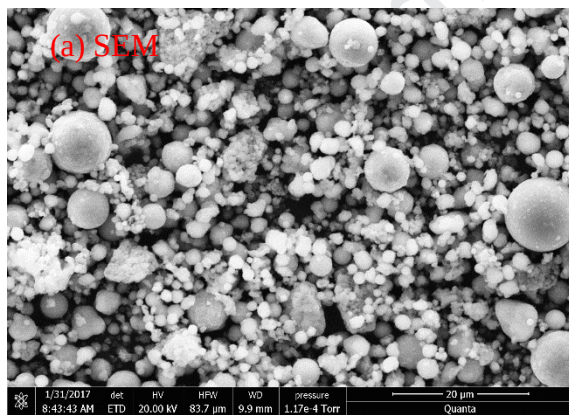
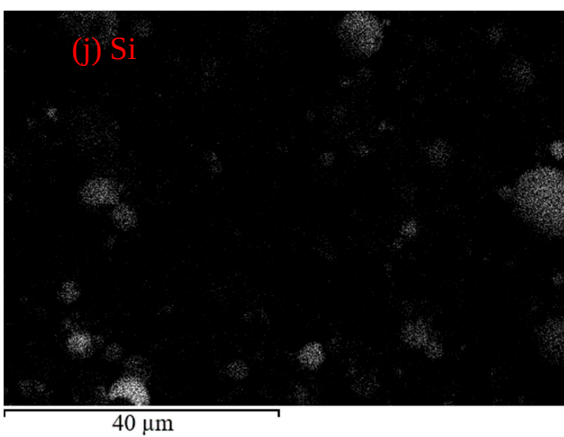
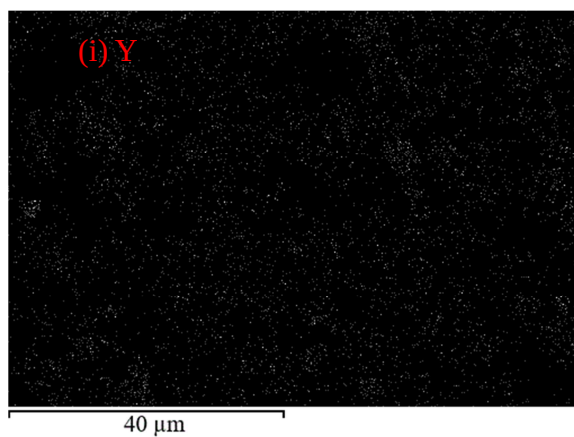
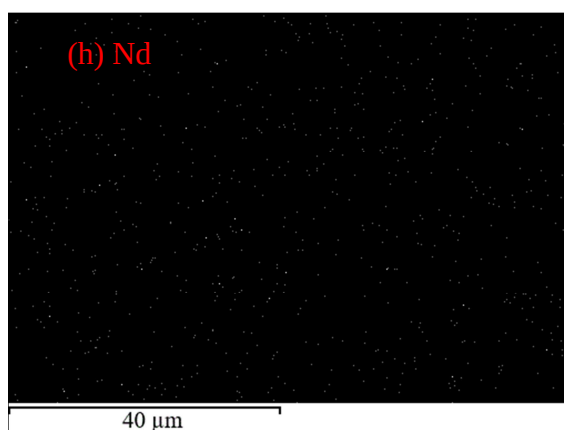
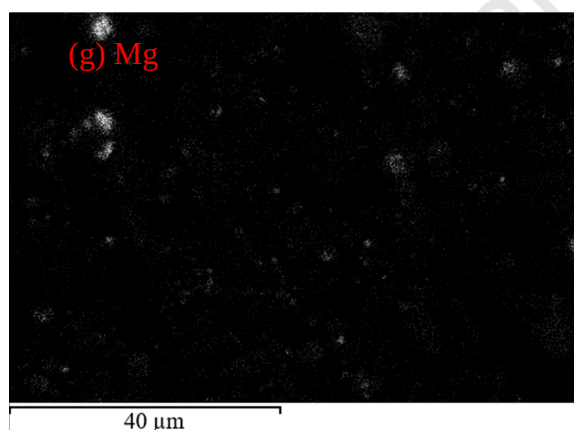
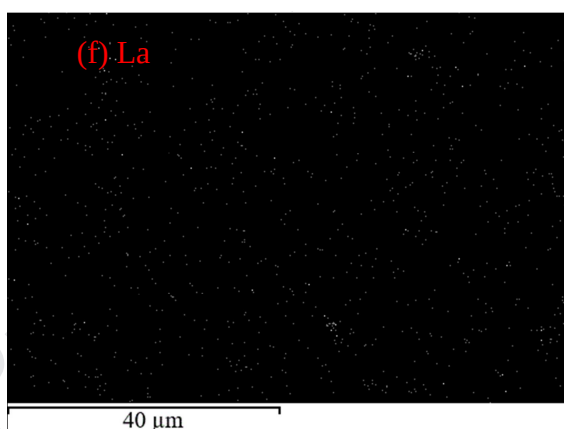
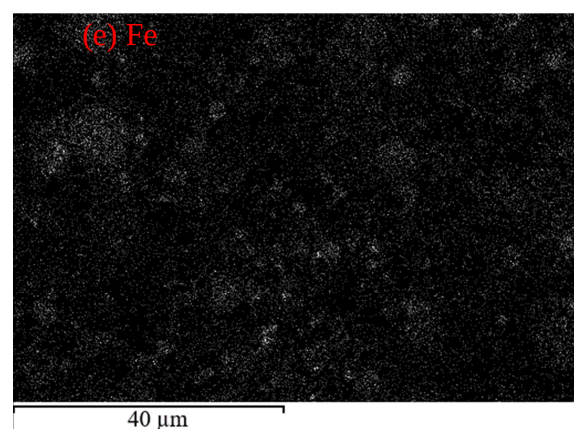
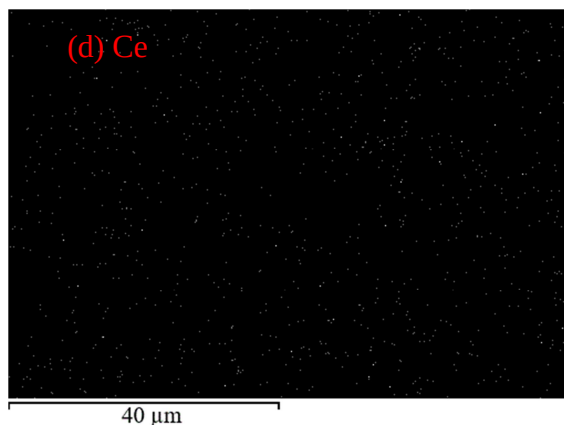
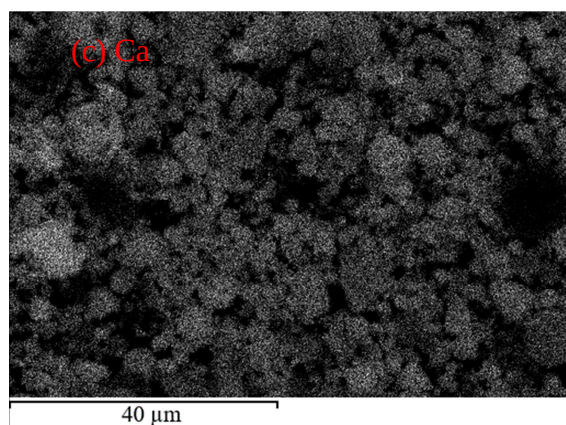
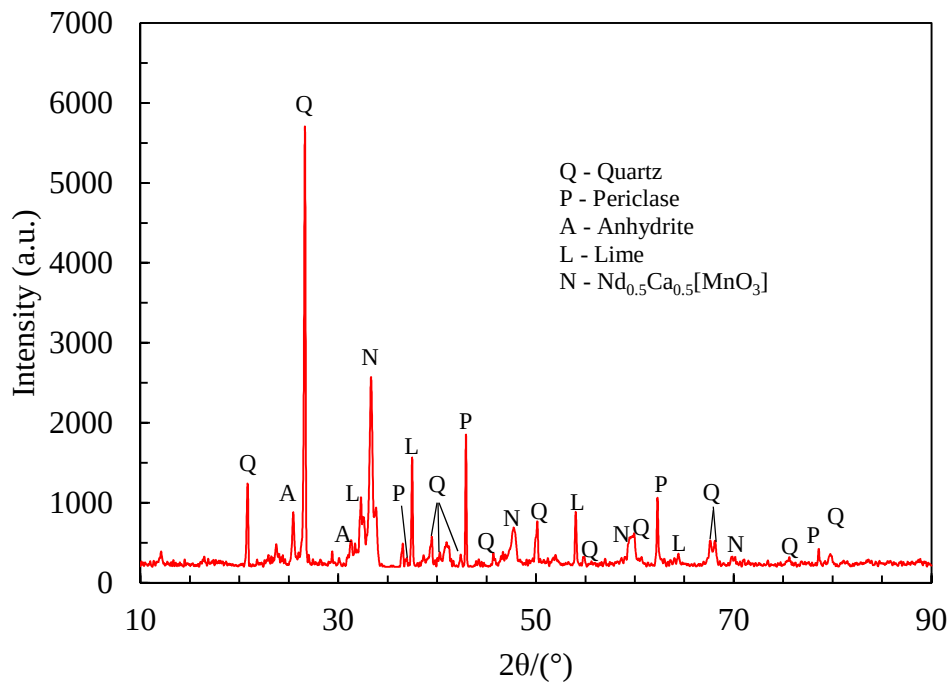


Figure 5 Correlation of total mineral concentrations and REY concentrations. The ash samples in the plot were sorted with ascending order of the REY concentrations.





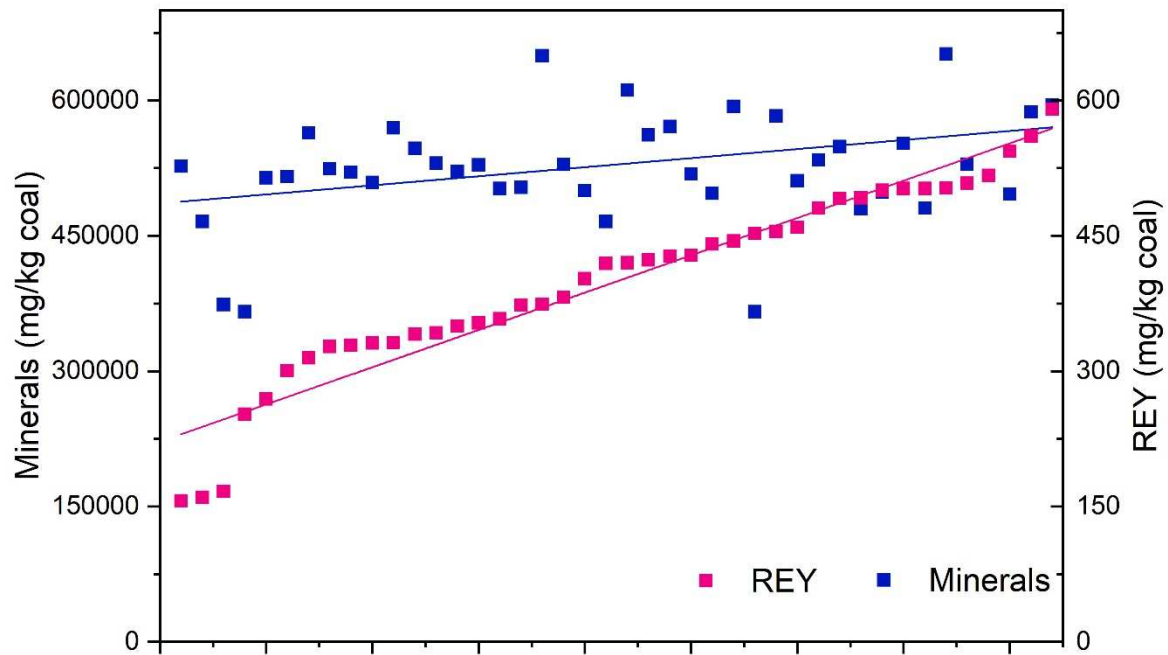
427 **Figure 6** SEM analysis of the coal fly ash (No. 21) with EDS analysis of elements including
 428 Al, Ca, Ce, Fe, La, Mg, Nd, Y, and Si
 429



430
 431 **Figure 7** Example of X-ray diffraction patterns of coal fly ash (NO. 21). The major
 432 components include quartz, periclase, anhydrite, lime, and neodymium-calcium-manganese
 433 oxide.
 434

435 Graphic abstract

436 The concentrations of rare earth elements derived from Powder River Basin coal are found to
437 be scattered. However, the analysis shows that the rare earth element concentration is
438 positively correlated to the mineral concentration, suggesting the form of minerals might
439 have impacts on the enrichment/detainment of rare earth elements which implies an
440 alternative way of rare earth element beneficiation from coal fly ash.



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