

Preliminary Assessment of the Economic Potential of Rare Earth Elements Associated with Coal in Wahau Formation

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Abstract

Coal and coal-associated materials are increasingly considered unconventional sources of rare earth elements and yttrium (REY), but concentration alone is insufficient to establish economic potential. This study assesses REY enrichment, composition, oxide-equivalent grade, and processing complexity in three Wahau low-rank coals and three laboratory-produced ash samples through preliminary comparative screening. Fifteen REY (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y) were quantified by ICP-MS. The assessment combines: (i) enrichment relative to world coal and coal-ash averages, (ii) the Seredin-Dai outlook coefficient and critical REY percentage, (iii) calculated rare-earth-oxide (REO) grade for ash, and (iv) literature-based technical processing complexity. Wahau coal contains 26.54-60.22 mg/kg REY, below the world-coal average of 68.47 mg/kg. Laboratory ash contains 109.44-767.93 mg/kg; Wahau Ash 2 is 1.90 times the world coal-ash average of 403.5 mg/kg and corresponds to approximately 913 mg/kg REO. However, critical REY percentages are only 11.83-18.09%, and none of the samples meet the 30-51% critical-REE composition window used for promising materials in the Seredin-Dai framework. Comparison with Indonesian coal, Indonesian CFA, and coal-gangue studies shows that coal-derived residues can attain substantially higher REY grades, although refractory aluminosilicate hosts commonly require activation and hydrometallurgical treatment. The results identify Wahau Ash 2 as the strongest concentration target, while confirming that grade, REY composition, and extractability must be evaluated together before full techno-economic analysis.

Keywords *Rare Earth Elements; Coal; Coal Ash; Coal Gangue; Economic Screening*

INTRODUCTION

Rare earth elements and yttrium (REY) in coal-bearing sequences reflect complex geological processes, including sediment provenance, volcanic input, peat-forming conditions, diagenesis, groundwater interaction, and post-depositional processes. REY may occur in clay minerals, phosphates, detrital and authigenic minerals, and partly with organic matter, particularly in low-rank coal. These modes of occurrence influence REY enrichment, redistribution, and

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recovery during beneficiation, combustion, and subsequent processing.

The low-rank characteristics of Indonesian coals, particularly their moisture and thermal behavior, may affect downstream processing and thermal treatment ([Haq et al., 2025](#)). Local REY enrichment has been reported in the Ombilin, South Sumatra, Pasir, and Barito coal basins, where terrigenous input, volcanic ash or tonstein, mineral matter, and post-depositional processes influence REY distribution ([Anggara et al., 2018](#); [Patria & Anggara, 2021](#); [Anggara et al., 2024](#)). Coal fly ash is increasingly considered a secondary REY resource, although its concentration and extractability vary with parent coal composition, combustion conditions, and mineral transformations during ash formation ([Shafiyurrahman et al., 2026](#); [Haq et al., 2026](#)).

The Wahau Formation is a relevant case because its low-rank coal is the primary geological host, whereas laboratory-produced ash is a combustion-enriched derivative. This study evaluates REY characteristics in Wahau coal and laboratory-produced ash and compares their potential with coal fly ash, coal gangue, and other coal-associated materials. The comparison aims to identify materials with the most favorable combination of REY enrichment, geological occurrence, and technical recoverability, supporting a broader assessment of coal-associated REY resources in Indonesia.

LITERATURE REVIEW

Geological occurrence of REY in coal-bearing sequences

A combination of geological processes controls rare earth elements and yttrium (REY) in coal-bearing sequences, including sediment provenance, volcanic input, peat accumulation, diagenesis, groundwater interaction, and hydrothermal alteration. These processes can introduce, redistribute, or locally enrich REY within coal seams and their associated strata. REY may occur in clay minerals, phosphates, accessory detrital phases, authigenic minerals, and, to some extent, in association with organic matter, particularly in low-rank coal. These variations in occurrence mode influence both total REY concentration and their behavior during beneficiation, combustion, and subsequent extraction ([Seredin & Dai, 2012](#); [Zhang et al., 2026](#)).

REY in Indonesian coal and coal-derived ash

Previous studies have identified REY enrichment in the Ombilin, South Sumatra, Pasir, and Barito basins, indicating the importance of terrigenous input, volcanic ash, mineral matter, and post-depositional processes in controlling REY distribution ([Anggara et al., 2018](#); [Patria & Anggara, 2021](#); [Anggara et al., 2024](#)). [Anggara et al. \(2018\)](#) demonstrated the influence of volcanic material in the Banko coalfield, where coal immediately beneath tonstein layers showed enhanced REY concentrations. This indicates that volcanic ash can act as both a direct source of REY and a reactive material that releases elements during alteration. [Anggara et al. \(2024\)](#) later reported REY concentrations of up to 194.56 mg/kg in the Tanjung Formation and showed that coal, roof, floor, and parting materials may all contain locally enriched REY.

Indonesian CFA studies indicate that ash mineralogy strongly influences REY distribution. [Shafiyurrahman et al. \(2026\)](#) reported Ce as the dominant REE and identified relationships between REE groups and SiO₂, Al₂O₃, and Fe₂O₃. [Haq et al. \(2026\)](#) further showed that alkaline desilication improves REE accessibility by disrupting the aluminosilicate matrix, followed by effective recovery through H₂SO₄–H₂O₂ leaching.

Coal gangue and other coal-associated materials

Coal gangue can become a secondary feedstock for critical-metal recovery, with REE concentrations reaching 324.28 mg/kg versus 66.22 mg/kg in associated coal ([Yu et al., 2022](#)). However, enrichment varies by deposit and requires site-specific characterization. Recovery

depends on mineral hosting, with clay-rich gangue and CFA often requiring grinding, thermal treatment, activation, or leaching (Wang et al., 2025; Zhang et al., 2026).

RESEARCH METHOD

Samples and Analytical Data

We selected six samples from the Wahau analytical dataset: three low-rank coal samples (Wahau Coal 1–3) and three laboratory-produced ash samples (Wahau Ash 1–3). Samples were randomly selected to minimize bias from unusually high REY concentrations and were intended only for exploratory comparison, not for deposit-scale resource estimation. Laboratory-produced ash was generated by heating coal-derived material at approximately 900 °C for 30–60 min. It is distinct from commercial coal fly ash (CFA), which forms under different combustion, residence-time, and particle-separation conditions. REY concentrations were determined by ICP-MS (iCAP-RQ, Thermo Fisher Scientific, ASX-560 autosampler) and reported in mg/kg for La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y.

The screening-level economic potential assessment considered REY enrichment, elemental composition, oxide-equivalent grade, and technical processing characteristics. A category-specific enrichment factor (EF) was calculated to compare Wahau coal and laboratory ash with global coal and coal-ash reference values (Eq. 1).

$$EF = \Sigma REY_{\text{sample}} / \Sigma REY_{\text{world-category}} \dots\dots\dots (Eq.1)$$

An EF greater than 1 indicates enrichment relative to the selected reference, whereas EF below 1 indicates lower concentration. Second, REY composition was evaluated using the market-oriented classification of Seredin and Dai (2012), consisting of critical REY (Nd, Eu, Tb, Dy, Er, and Y), uncritical REY (La, Pr, Sm, and Gd), and excessive REY (Ce, Ho, Tm, Yb, and Lu). The outlook coefficient and critical REY percentage were calculated as in Eqs. 2 and 3.

$$Coutl = (Nd + Eu + Tb + Dy + Er + Y) / (Ce + Ho + Tm + Yb + Lu) \dots\dots\dots (Eq.2)$$

$$Critical\ REY\ (\%) = 100 \times (Nd + Eu + Tb + Dy + Er + Y) / \Sigma REY \dots\dots\dots (Eq.3)$$

The original Seredin-Dai promising window (Coutl 0.7–1.9; critical REY 30–51%) was used as the principal comparison without forcing intermediate samples into categories. Ash REY concentrations were converted to oxide equivalents and summed as ΣREO using stoichiometric factors for individual RE oxides and Y_2O_3 . Results were compared with the 1000 mg/kg REO ash cut-off (Seredin & Dai, 2012; Eq. 4).

$$\Sigma REO = \Sigma (Ci \times Fi) \dots\dots\dots (Eq.4)$$

where C_i is the concentration of element i and F_i is the stoichiometric mass-conversion factor from the element to its conventional oxide.

Finally, technical processing complexity was assessed qualitatively from peer-reviewed literature based on the dominant REY host phase, the pretreatment required before leaching, direct-leaching behavior, and impurity-management requirements. This comparison distinguished the relative processing challenges of raw coal, laboratory-produced ash/CFA, coal gangue, and other coal-associated materials.

FINDINGS AND DISCUSSION

REY concentrations and distribution in Wahau Formation

Table 1 presents the REY concentrations of the selected Wahau samples. The dataset represents a preliminary subset of the available analytical data and is used for an initial geochemical and comparative assessment. Therefore, the results are interpreted as indicative of the selected samples and are not intended to represent the full REY variability of the Wahau Formation or to support deposit-scale resource estimation.

Table 1. Preliminary REY concentrations in selected Wahau coal and laboratory-produced ash samples

Element	Wahau Coal 1 (mg/kg)	Wahau Coal 2 (mg/kg)	Wahau Coal 3 (mg/kg)	Wahau Ash 1 (mg/kg)	Wahau Ash 2 (mg/kg)	Wahau Ash 3 (mg/kg)
La	4.320	8.814	8.374	6.338	121.256	42.542
Ce	5.043	8.238	2.867	20.814	114.383	19.140
Pr	7.841	20.050	8.116	45.862	272.082	57.401
Nd	1.003	2.605	1.282	4.950	30.392	7.411
Sm	3.884	10.250	6.231	19.540	118.430	32.241
Eu	0.864	2.245	1.898	3.283	24.522	10.014
Gd	0.271	0.541	0.545	0.759	6.316	2.882
Tb	1.144	2.880	2.533	4.033	33.285	12.119
Dy	0.156	0.360	0.342	0.374	3.796	1.524
Ho	0.878	1.991	1.741	1.501	19.353	7.419
Er	0.170	0.348	0.303	0.248	3.534	1.221
Tm	0.457	0.935	0.694	0.575	9.455	2.781
Yb	0.063	0.122	0.079	0.710	1.481	0.318
Lu	0.398	0.740	0.415	0.392	8.331	1.753
Y	0.050	0.099	0.061	0.059	1.318	0.265
ΣREY	26.542	60.218	35.481	109.438	767.934	199.031

The three coal samples contain ΣREY concentrations ranging from 26.542 to 60.218 mg/kg, with Wahau Coal 2 showing the highest concentration, followed by Wahau Coal 3 and Wahau Coal 1. Laboratory-produced ash contains substantially higher ΣREY concentrations, ranging from 109.438 to 767.934 mg/kg. Wahau Ash 2 is particularly enriched, exceeding Wahau Ash 3 by more than three times and Wahau Ash 1 by approximately seven times.

According to [Seredin and Dai \(2012\)](#), all samples are LREY-dominated. LREY account for 75.7–83.2% in coal and 79.8–89.1% in ash, while MREY contribute 9.4–15.2% and 7.8–13.5%, and HREY 6.9–9.1% and 3.1–6.8%, respectively.

Table 2. Geochemical classification of LREY (La–Sm), MREY (Eu, Gd, Tb, Dy, and Y), and HREY (Ho–Lu)

Sample	ΣREY (mg/kg)	LREY (mg/kg)	MREY (mg/kg)	HREY (mg/kg)
Wahau Coal 1	26.542	22.091	2.485	1.966
Wahau Coal 2	60.218	49.957	6.125	4.136
Wahau Coal 3	35.481	26.870	5.379	3.232
Wahau Ash 1	109.438	97.504	8.508	3.426

Sample	Σ REY (mg/kg)	LREY (mg/kg)	MREY (mg/kg)	HREY (mg/kg)
Wahau Ash 2	767.934	656.543	69.237	42.154
Wahau Ash 3	199.031	158.735	26.804	13.492

Pr is the dominant individual element in five of the six samples, including Wahau Coal 1, Wahau Coal 2, and all three laboratory ash samples. Wahau Coal 3 differs slightly, with La marginally exceeding Pr. Sm, La, and Ce also contribute substantially to the total REY inventory. The consistent dominance of LREY suggests that the preliminary Wahau dataset is characterized by preferential enrichment of the lighter REY fraction rather than by HREY enrichment.

The most evident distinction between the two material groups is the higher REY concentration in laboratory-produced ash. This pattern is consistent with removing combustible organic matter during furnace treatment and retaining relatively nonvolatile inorganic components in the residual ash.

REY enrichment and composition-based resource potential

Pr is the dominant individual element in five of the six samples, including Wahau Coal 1, Wahau Coal 2, and all three laboratory ash samples. Wahau Coal 3 differs slightly, with La marginally exceeding Pr. Sm, La, and Ce also contribute substantially to the total REY inventory. The consistent dominance of LREY indicates that the preliminary Wahau dataset is characterized by preferential enrichment of the lighter REY fraction rather than HREY enrichment. The most evident distinction between the two material groups is the higher REY concentration in laboratory-produced ash. This pattern is consistent with the removal of combustible organic matter during furnace treatment and the retention of relatively nonvolatile inorganic components in the residual ash, resulting in apparent REY concentration in the ash fraction.

Table 3. Preliminary screening parameters for REY resource potential

Sample	Σ REY (mg/kg)	EF	Critical REY (mg/kg)	Critical REY (%)	C _{outl}	Σ REO (mg/kg)
Wahau Coal 1	26.542	0.39	3.387	12.76	0.50	31.56
Wahau Coal 2	60.218	0.88	8.537	14.18	0.71	71.48
Wahau Coal 3	35.481	0.52	6.419	18.09	1.11	41.84
Wahau Ash 1	109.438	0.27	12.947	11.83	0.54	130.68
Wahau Ash 2	767.934	1.90	96.847	12.61	0.63	913.23
Wahau Ash 3	199.031	0.49	32.554	16.36	1.04	235.47

The market-oriented composition provides a different perspective from total REY concentration. Following [Seredin and Dai \(2012\)](#), critical REY comprise Nd, Eu, Tb, Dy, Er, and Y, contributing 12.76–18.09% in coal and 11.83–16.36% in laboratory ash. These proportions fall below the critical-REY range of approximately 30–51% proposed by Seredin and Dai, mainly because of strong contributions from Pr, Sm, La, and Ce. The calculated Coutl values range from

0.50–1.11 in coal and 0.54–1.04 in laboratory ash. Wahau Coal 3 and Wahau Ash 3 show the highest values, indicating a more favorable balance between critical and excessive REY; however, their critical REY percentages remain low. Thus, none of the selected Wahau samples satisfies both parameters of the original promising cluster. This represents historical compositional screening rather than contemporary critical-mineral classification.

Conversion to oxide equivalents highlights Wahau Ash 2, with ΣREO of approximately 913 mg/kg, approaching the 1000 mg/kg preliminary ash-grade benchmark (Seredin & Dai, 2012), but remaining below it. Economic viability requires resource size, beneficiation potential, recovery efficiency, and environmental constraints.

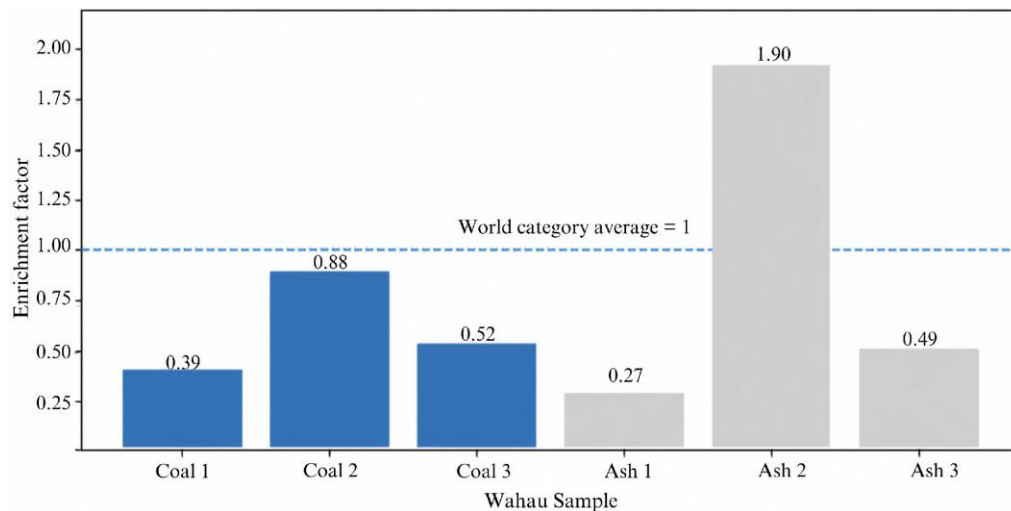


Figure 1. Enrichment factor of Wahau samples relative to the Ketris and Yudovich (2009) world average for the corresponding material category (coal or coal ash).

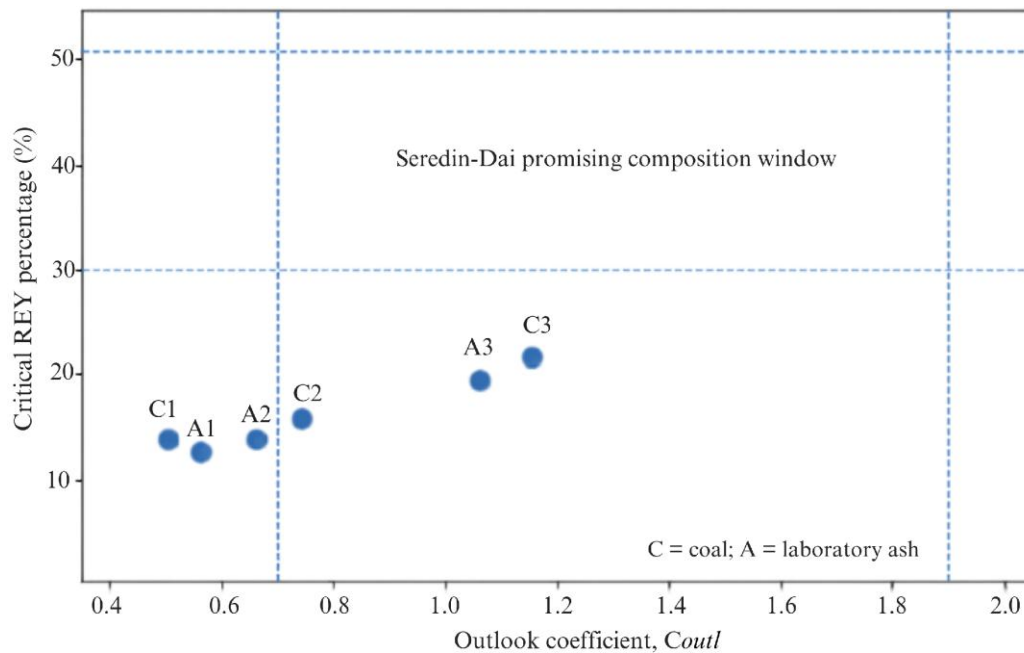


Figure 2. Wahau samples plotted against the original Seredin-Dai promising composition window

Technical processing complexity and implications for economic potential

The economic potential of coal-associated REY resources depends not only on grade but also on mineralogical occurrence and processing complexity (Table 4). Raw coal generally presents greater extraction challenges because REY occur at low concentrations within a carbonaceous matrix and may be distributed among mineral and organic associations. Direct recovery from raw coal is therefore commonly less favorable than from mineral-rich coal-associated materials (Zhang et al., 2026).

Coal-derived ash and CFA benefit from inorganic concentration during combustion, although REY may become incorporated into refractory aluminosilicate phases. In Indonesian Class F CFA, alkaline desilication disrupted the aluminosilicate matrix and increased REE accessibility before acid leaching. Coal gangue presents similar challenges because REY are frequently associated with kaolinite and clay minerals, requiring grinding and thermal or alkaline activation. CFA recovery commonly requires pre-concentration, matrix activation, and hydrometallurgical treatment, while clay-rich gangue may benefit from physical separation and thermal activation before leaching (Zhang et al., 2022; Tian et al., 2025; He et al., 2026).

For the preliminary Wahau dataset, laboratory-produced ash appears more favorable than raw coal based on REY concentration. However, economic attractiveness requires mineralogical characterization, leaching tests, recovery, reagent consumption, and energy assessment.

Table 4. Literature-informed technical processing complexity for major coal-associated REY feedstocks

Material	Grade tendency	Likely processing route	Indicative technical complexity	Supporting literature
Raw coal	Generally low and heterogeneous; Wahau: 26.5–60.2 mg/kg	Beneficiation to concentrate mineral matter, followed by hydrometallurgical treatment where appropriate	High for direct extraction	Seredin & Dai (2012); Zhang et al. (2026)
Laboratory ash/ CFA	Generally enriched relative to parent coal; Wahau laboratory ash: 109.4–767.9 mg/kg	Physical pre-concentration, matrix activation/desilication or roasting, acid leaching, and downstream separation	Moderate–high; strongly matrix dependent	Haq et al. (2026); He et al. (2026); Tian et al. (2025)
Coal gangue	Highly variable; approximately 97 to >1000 mg/kg in selected published cases	Selective grinding or physical separation, thermal/alkaline activation, followed by leaching	Moderate–high; mineralogy dependent	Zhang et al. (2022); Wang et al. (2025); Yu et al. (2022)
Roof/floor/parting/tonstein	May contain locally enriched REY	Potential selective targeting or segregation followed by beneficiation and	Moderate–high; strongly	Anggara et al. (2018, 2024);

Material	Grade tendency	Likely processing route	Indicative technical complexity	Supporting literature
	horizons	hydrometallurgy	dependent on grade continuity and mineralogy	Seredin & Dai (2012)

CONCLUSIONS

The selected Wahau coal samples contain 26.54–60.22 mg/kg Σ REY and show limited enrichment, whereas laboratory-produced ash displays greater variability. Wahau Ash 2 records the strongest preliminary signal, with 767.93 mg/kg Σ REY, an EF of 1.90, and approximately 913 mg/kg REO. However, all samples are dominated by LREY and contain relatively low proportions of critical REY, indicating that total grade alone is insufficient to define resource potential. Mineralogical occurrence and technical recoverability remain important constraints, particularly for REY hosted in aluminosilicate glass or clay-rich phases.

LIMITATIONS & FURTHER RESEARCH

This study is limited by the small preliminary dataset, the absence of paired coal–ash samples, ash-yield and resource-tonnage data, and direct recovery and process-cost measurements. Therefore, the results should be interpreted as sample-specific rather than representative of the entire Wahau Formation. Further research should include stratigraphically controlled sampling, paired coal-to-ash mass balance, mineralogical characterization, recovery testing, and subsequent techno-economic evaluation.

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