

KARAKTERISASI PENGAYAAN UNSUR LOGAM TANAH JARANG BERDASARKAN VARIASI NILAI KALORI ENDAPAN BATUBARA

CHARACTERIZATION OF RARE EARTH ELEMENTS ENRICHMENT BASED ON COAL CALORIFIC VALUE VARIATIONS

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Abstrak

Akselerasi transisi energi bersih memicu lonjakan permintaan Logam Tanah Jarang (LTJ) global, sementara rantai pasoknya sangat bergantung pada negara produsen utama. Keterbatasan ini mendorong eksplorasi sumber LTJ alternatif, khususnya pada endapan batubara serta limbah *Fly Ash* dan *Bottom Ash* (FABA). Meskipun studi LTJ pada lapisan batubara dan FABA telah banyak dilakukan, penelitian yang secara langsung menghubungkan pengaruh nilai kalori batubara terhadap pengayaan LTJ masih sangat terbatas. Penelitian ini hadir untuk mengisi celah tersebut dengan menganalisis korelasi antara kualitas energi batubara (nilai kalori) dan ketersediaan LTJ pada Formasi Sinamar di wilayah konsesi PT Kuansing Inti Makmur. Metode yang digunakan meliputi analisis proksimat standar ASTM untuk parameter kualitas batubara serta pengujian *Inductively Coupled Plasma-Optical Emission Spectroscopy* (ICP-OES) untuk mengukur konsentrasi 10 unsur LTJ tertarget. Hasil analisis proksimat menunjukkan sampel KS100 memiliki kadar abu tinggi (24,11% AR) dengan nilai kalori lebih rendah (3.560 kcal/kg AR), sedangkan sampel KS300 memiliki kadar abu lebih rendah (10,36% AR) dan nilai kalori lebih tinggi (4.866 kcal/kg AR). Hasil uji ICP-OES mengonfirmasi temuan penting bahwa pengayaan LTJ justru lebih signifikan pada sampel batubara dengan kualitas energi atau nilai kalori yang lebih tinggi (KS300). Unsur Cerium (Ce) dan Lanthanum (La) menjadi LTJ Ringan paling dominan dengan kadar Ce mencapai 114 ppm pada KS100 dan 150 ppm pada KS300. Sementara unsur bernilai tinggi untuk komponen motor kendaraan listrik seperti Neodymium (Nd) mencapai 91,76 ppm pada KS300, hampir dua kali lipat dari KS100 (50,51 ppm). Konsentrasi LTJ total pada material *parting* makroskopis tercatat lebih rendah (180,01 ppm) dibandingkan fraksi anorganik di dalam batubara itu sendiri. Kesimpulannya, keterbaharuan riset ini membuktikan bahwa pengayaan LTJ tidak berkorelasi linier dengan penurunan nilai kalori (atau besarnya kadar abu total). Sebaliknya, pengayaan ini diduga dipengaruhi oleh tatanan geologi yang spesifik serta dinamika geokimia pada batasan lapisan batulempung (*claystone*) yang berdekatan

Kata kunci: Logam Tanah Jarang, Nilai Kalori, Analisis ICP, Pengkayaan

Abstract

The accelerated transition toward clean energy has triggered a global surge in demand for Rare Earth Elements (REEs), while its supply chain remains heavily dependent on a single dominant producing nation. This constraint has compelled extensive exploration into alternative REEs feedstocks, particularly within coal deposits and Coal Combustion Residuals (CCRs) or Fly Ash and Bottom Ash (FABA). Although multiple studies on REEs occurrences within coal seams and FABA have been conducted, research directly correlating the influence of coal calorific value to REEs enrichment remains profoundly limited. This study addresses this critical research gap by analyzing the correlation between coal energy quality (calorific value) and REEs occurrences within the Oligocene Sinamar Formation at the PT Kuansing Inti Makmur concession area. The methodology integrated ASTM standard proximate analysis to determine fundamental coal quality parameters and Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) to quantify the concentrations of 10 targeted REEs elements. The proximate results indicated that sample KS100

exhibits a high ash yield (24.11% AR) with a lower gross calorific value (3,560 kcal/kg AR). Conversely, sample KS300 is characterized by a lower ash content (10.36% AR) and a higher calorific value (4,866 kcal/kg AR). Crucially, the ICP-OES analytical data revealed a compelling trend: REEs enrichment is notably more pronounced in the higher-energy quality coal seam (KS300). Cerium (Ce) and Lanthanum (La) emerged as the most dominant Light Rare Earth Elements (LREEs) in both horizons, with Ce concentrations reaching 114 ppm in KS100 and 150 ppm in KS300. Highly strategic elements essential for permanent magnet motors in electric vehicles, such as Neodymium (Nd), reached 91.76 ppm in KS300, which is nearly double the 50.51 ppm recorded in KS100. Furthermore, the total REEs concentration within the macroscopic parting layer was significantly lower (180.01 ppm) compared to the dispersed inorganic fraction within the coal matrices themselves. In conclusion, the novelty of this research demonstrates that REEs enrichment does not correlate linearly with the degradation of calorific value or total ash yield. Instead, it is suggested to be influenced by specific geological settings and the geochemical dynamics at the adjacent claystone boundaries.

Keywords: Rare Earth Elements, Calory Value, ICP Analysis, Enrichment

I. INTRODUCTION

Indonesia is committed to achieving its Net Zero Emissions (NZE) target by 2060. To realise this objective, the acceleration of the transition from fossil fuels to clean energy is essential. In parallel with this, global trends indicate a rapid shift toward green energy, driven by the significant development and demand for environmentally friendly electric vehicles.

Rare Earth Elements (REEs) consist of the 15 elements in the lanthanide series (Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium, and Lutetium), along with Scandium and Yttrium, totalling 17 elements. The primary application of REEs in the electric vehicle (EV) sector is in the production of high-performance permanent magnets and advanced battery components. Specifically, elements such as Neodymium, Praseodymium, and Dysprosium are critical for manufacturing permanent magnet motors, while others contribute significantly to the efficiency and stability of EV battery systems [1].

China accounts for approximately 95% of global Rare Earth Element (REEs) production. In the period of 2011–2012, China restricted its REEs exports by 35%, reducing the volume from 50,000 tonnes to 30,000 tonnes. This policy triggered a global supply crisis, significantly impacting multiple nations, including the United States, which relied heavily on Chinese supplies [2]. This scarcity, coupled with the high level of dependency on a single primary source, has compelled various countries to explore and identify new potential REEs deposits.

The potential for REEs deposits in Indonesia is closely associated with granitoid formations in the Bangka tin deposits, where REEs are found within

monazite and xenotime as accessory minerals to tin. Characterization results indicate that monazite from these tin tailing deposits contains an average of Ce (28.2%), La (12.9%), Nd (9.7%), Pr (5.2%), and Gd (3.9%). In contrast, xenotime is characterized by major elements such as Y (29.5%), Dy (7.7%), and Gd (2.6%) [3]. Beyond tin deposits, recent studies have identified REEs occurrences in coal. Research at the PT Prima Mulia Sarana Sejahtera coal mine revealed REEs concentrations of Ce (6.0153 ppm), Gd (0.0309 ppm), La (0.1979 ppm), Sc (0.1049 ppm), and Y (0.3109 ppm) [4]. Furthermore, a 2023 study on Fly Ash and Bottom Ash within the Low Rank Coal of Muara Enim Formation identified the presence of several REEs elements, including Y (3.03 ppm), Nd (2.88 ppm), Gd (2.58 ppm), Sm (2.33 ppm), Ce (2.14 ppm), Sc (0.84 ppm), La (0.71 ppm), Pr (0.29 ppm), and Eu (0.21 ppm) [5].

Coal composition should have both organic and inorganic components. The organic matters are combustible and generate energy during the power generation process in coal-fired power plants (PLTU), whereas the inorganic matters remain unburned, forming Fly Ash and Bottom Ash (FABA). REEs occurrences are associated with the inorganic matters within the coal [6]. This is consistent with previous research on FABA, which identified REEs concentrations in bottom ash comprising Ce (64.2 ppm), Nd (31.2 ppm), La (25.4 ppm), Y (23.3 ppm), and Sc (20.1 ppm), while fly ash contained only Ce (22.2 ppm) [7].

Consequently, a higher proportion of inorganic matters in coal seams suggests a greater potential for REEs enrichment. However, specific studies examining the direct correlation between these two variables remain limited. In proximate analysis, inorganic matters are identified as ash content. High ash content is generally undesirable, as it significantly

reduces the calorific value of the coal [8], often necessitating coal washing processes. While coal washing incurs additional operational costs, the potential recovery of REEs associated with these inorganic rejects presents a symbiotic opportunity to simultaneously improve calorific value and extract high-value minerals.

The inverse relationship between ash content and calorific value suggests a potential correlation between the energy quality of coal and its REEs concentrations. As higher ash content typically leads to a reduction in calorific value, it simultaneously increases the presence of the inorganic host minerals where REEs are primarily sequestered. Therefore, the objective of this research is to analyze the correlation between calorific value and the occurrence of REEs. This study specifically evaluates whether variations in calorific value can serve as a reliable indicator for the presence of these critical elements in coal seams.

II. LITERATUR REVIEW

A. Regional Geology

The study area is geographically situated on the border between Bungo Regency in Jambi Province and South Solok Regency in West Sumatra Province. Geologically, this region lies within the South Sumatra Basin, a major Tertiary sedimentary basin in western Indonesia. The formation of this basin was governed by complex tectonic activities, specifically extensional fault movements triggered by the subduction of the Indian Ocean Plate and the Eurasian Continental Plate. Specifically, the targeted coal seams are part of the Sinamar Formation, which represents a critical depositional episode within the sub-basin framework in Figure 1.

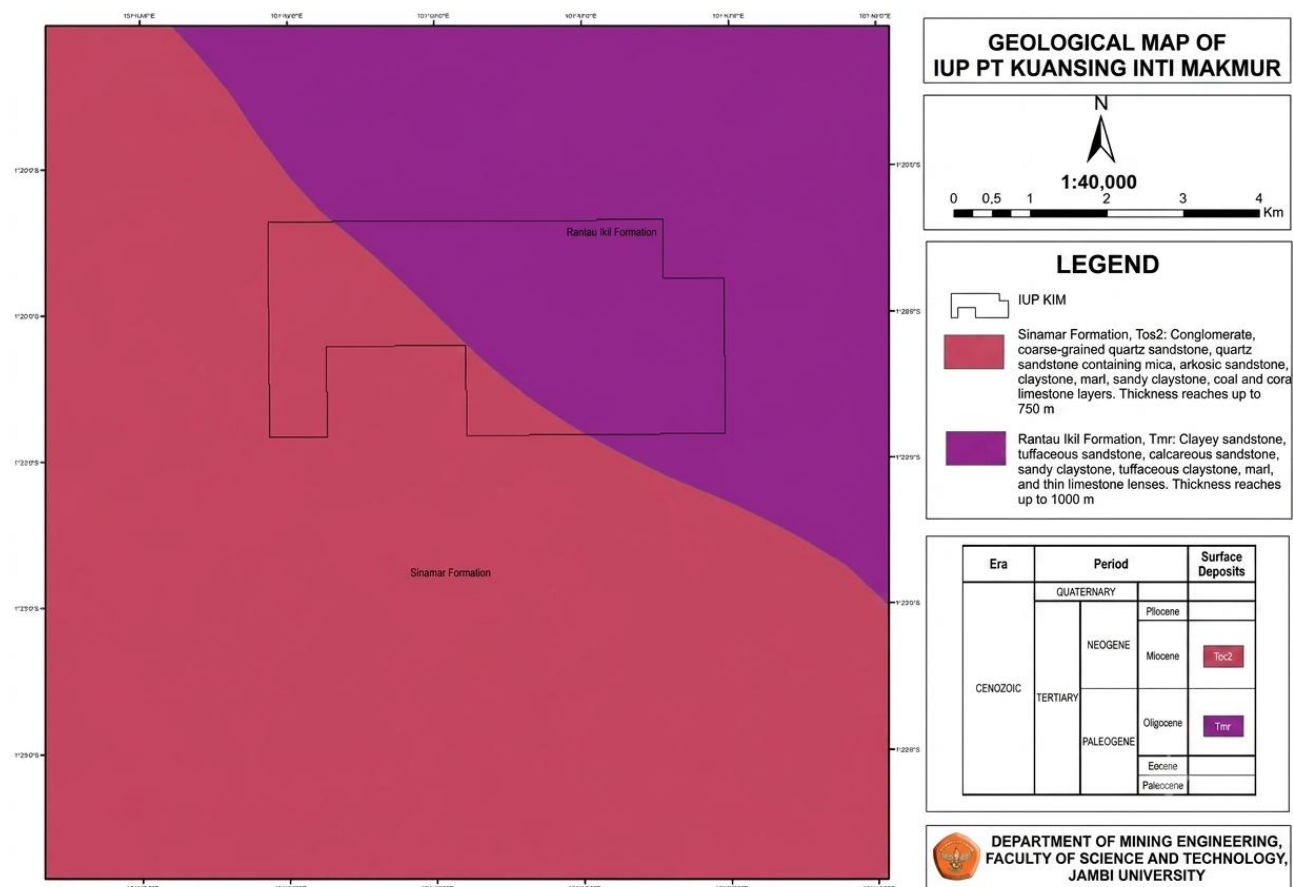


Figure 1. Regional Geology

The regional stratigraphy of the Sinamar Formation is characterized by a thick terrestrial to marginal marine succession, comprising an evolutionary sequence of shale, claystone, siltstone,

and sandstone, interbedded with well-developed coal seams. Based on regional geological syntheses, this formation was primarily deposited within a fluvial-deltaic environment, where shifting river channels,

floodplains, and extensive peat-swamp communities coexisted. This dynamic depositional setting provided the necessary accommodation space and organic influx for prolonged peat accumulation, which subsequently underwent coalification.

The Oligocene-aged Sinamar Formation constitutes the oldest sedimentary unit within this basin framework, resting unconformably over Jurassic granitoid basement rocks that serve as the fundamental floor of the basin. The Sinamar Formation exhibits a total stratigraphic thickness of up to 750 meters. It is subsequently overlain unconformably by the younger Oligocene to Miocene-aged Rantaukil Formation.

B. Study on Rare Earth Elements in Coal

According to the Ministry of Energy and Mineral Resources (2019) [9], as outlined in the Potensi Logam Tanah Jarang report, Rare Earth Elements (REEs) are classified as critical minerals consisting of a group of 17 chemical elements. This suite encompasses the entire lanthanide series, comprising Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), and Lutetium (Lu) alongside Scandium (Sc) and Yttrium (Y).

Rare Earth Elements

by Geology.com

H	Rare Earth Elements																He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt									
Lanthanides																	
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu																	
Actinides																	
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr																	

Figure 2. Rare Earth Elements within Periodic Table (<http://geology.com/articles/rare-earth-elements/>)

Due to their unique geochemical properties and highly dispersed occurrences, these 17 elements are recognized as strategic minerals characterized by their scarcity and low economic concentration in conventional ores. The spatial distribution and configuration of these REEs within the periodic table of elements are illustrated in Figure 2, the REEs belongs to yellow column and row. Several studies have been initiated to identify the occurrence and

distribution of rare earth elements (REEs) within coal deposits, focusing on varying genetic mechanisms and geological settings:

First, investigated the identification of rare earth elements within the coal seams at PT Prima Mulia Sarana Sejahtera. In their study area, the presence of REEs within the coal horizons was influenced by the intrusion of igneous andesitic parent rocks. This andesitic intrusion was documented to enhance the calorific value of the coal while concurrently introducing elevated trace element concentrations. The study utilized Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) and petrographic analyses, specifically targeting five elements: Cerium (Ce), Gadolinium (Gd), Lanthanum (La), Scandium (Sc), and Yttrium (Y). Additionally, Scanning Electron Microscopy (SEM) was employed to characterize the internal mineral morphology. The laboratory results revealed a cumulative REEs concentration of 269.80 ppm within the intruded coal samples, with Ce exhibiting the highest individual concentration at 61.54 ppm [4].

Second, evaluated the concentrations of rare earth elements and yttrium (REY) within the Banko coalfield of the South Sumatra Basin, specifically assessing the geochemical contribution of tonstein layers. The Banko coalfield serves as an ideal setting for studying REY enrichment due to the documented presence of tuffaceous mudstone (tonstein) horizons, which are hypothesized to enrich the adjacent coal matrices. The methodology integrated thin-section and polished-section petrography, X-ray Diffraction (XRD), Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES), and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The findings concluded that the studied tonsteins originated from volcanic precursors, falling into both silicic and alkalic classifications. Samples retrieved directly beneath the silicic tonstein layers exhibited elevated aluminum (Al) and silicon (Si) yields alongside the highest REY concentrations. These data underline the viability of extracting critical metals from combustion residues, given that the REY content in the fly ash and bottom ash was found to be approximately tenfold higher than that of the raw feed coal [10].

Finally, addressed coal deposits as highly prospective alternative feedstocks for lanthanides and yttrium [11]. Significantly high REY concentrations (>0.1 %) have been observed globally across various coal seams, ash residues, roof/floor strata, and basement rocks.

The study classified REY enrichment within coal basins into four distinct genetic types:

1. Terrigenous type, governed by the surface water influx of detrital material;
2. Tuffaceous type, associated with the deposition and subsequent leaching of acidic or alkalic volcanic ashfall;
3. Infiltration type, driven by the circulation of meteoric and meteoric-derived groundwater; and
4. Hydrothermal type, influenced by the ascending flow of thermal fluids and deep-seated mineralized solutions.

The research noted that stratified and cross-cutting REY mineralizations can manifest both within the coal matrix and the adjacent host rocks, with tuffaceous and hydrothermal types displaying prominent variations in geological settings, orebody geometries, and distribution patterns. The study concluded that coal ash residues containing REY grades comparable to conventional economic ores are widely distributed across global coal fields. Consequently, the resource assessment and byproduct recovery of REEs from coal exploitation represent a highly promising pathway to fulfill the industrial demand for these critical metals.

III. RESEARCH METHODS

This study is classified as descriptive quantitative research, which focuses on the systematic measurement and quantification of specific chemical parameters to characterize geological occurrences. The primary objective is to investigate the concentrations of rare earth elements (REEs) across variations in coal quality and associated lithologies, establishing an empirical baseline for trace element distribution within the targeted deposit.

A. Sample Collection and Field Preparation

The sampling process was conducted within the mining concession of PT Kuansing Inti Makmur. Coal Samples were collected from two separate coal seams, the upper coal seam (KS100) and the lower coal seam (KS300), as well as from the middle coal seam (KS200) interbedded parting layer, identified as Parting in Figure 3.

The field sampling utilized the grab sampling method to collect a gross mass of approximately 5 kg for each target lithological unit to ensure adequate material for multiple laboratory procedures. To ensure homogeneity and reduce the bulk sample mass into a representative subset suitable for laboratory requirements, the collected materials underwent an

immediate field preparation stage using the coning and quartering technique in Figure 4.



Figure 3. Stratigraphic position of the seam parting; the image displays the KS200 seam (acting as the middle parting zone) situated vertically between the upper coal layer (KS100) above it and the lower coal layer (KS300) beneath it.

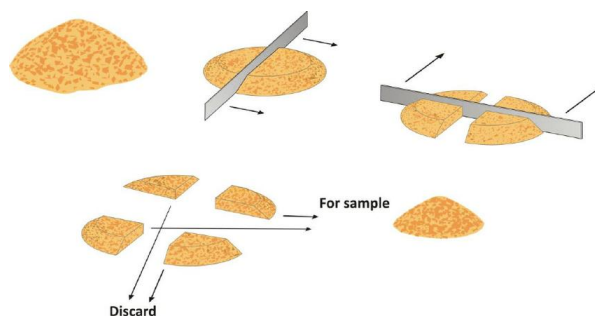


Figure 4. Coning and Quartering Method.

The 5 kg gross sample was piled into a uniform cone, flattened into a circular layer, and divided into four equal quarters. Two diagonally opposite quarters were selected and combined, while the remaining two were discarded. This operational cycle was repeated systematically until a homogenous composite sample of the required weight was secured for subsequent analytical testing.

B. Laboratory Analysis and Testing Procedures

The homogenized samples were distributed to specialized institutional laboratories to evaluate their fundamental coal quality parameters and trace element concentrations:

1. Proximate Analysis

The fundamental coal quality testing was carried out at the Laboratory Pengujian Batubara, Balai Diklat Tambang Bawah Tanah (BDTBT) Sawahlunto. A total of two representative coal samples were analyzed, comprising one sample from

the KS100 seam and one sample from the KS300 seam. This analysis was conducted to determine key parameters including Total Moisture (TM), Inherent Moisture (IM), Volatile Matter (VM), Ash Content, Fixed Carbon (FC), and Total Sulfur, along with the Gross Calorific Value (CV). The analytical procedures strictly adhered to the American Society for Testing and Materials (ASTM) standard protocols:

- Total Moisture & Inherent Moisture: Determined via thermal drying methods according to ASTM D3302-19 and ASTM D3173-17, respectively.
- Ash Content: Measured by complete sample combustion in a muffle furnace at 700–750°C following ASTM D3174-12.
- Volatile Matter & Fixed Carbon: Evaluated through high-temperature devolatilization under oxygen-free conditions based on ASTM D3175-20 and ASTM D3172-13.
- Gross Calorific Value: Quantified using an adiabatic bomb calorimeter in compliance with ASTM D5865-19 to evaluate the thermal energy density.

2. Inductively Coupled Plasma (ICP) Analysis

To identify and quantify the concentrations of Rare Earth Elements (REEs), a subset of three samples was sent to the Lab Pengujian Tekmira, Bandung. To ensure consistency and representativeness, the two coal samples selected for this analysis were identical to those utilized in the proximate analysis (one from the KS100 seam and one from the KS300 seam), supplemented by one parting sample from the KS200 layer. The trace element characterization followed a strict multi-step geochemical analytical procedure:

- Sample Digestion: The coal ash and parting residues were subjected to complete acid dissolution (utilizing a combination of strong mineral acids such as HF, HNO₃, and HCl) to completely break down the silicate and inorganic matrices, converting the bound REEs into an aqueous solution.
- Spectrometric Measurement: The digested solution was analyzed using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES). This quantitative analysis was specifically restricted to 10 targeted REEs elements, comprising Cerium (Ce), Europium (Eu), Gadolinium (Gd), Lanthanum (La), Neodymium (Nd), Praseodymium (Pr), Scandium (Sc), Samarium (Sm), Dysprosium (Dy), and Yttrium

(Y). The high-temperature plasma argon gas atomized and ionized the sample, allowing for the precise measurement of these specific lanthanides and associated elements, with the final concentrations calibrated and expressed in parts per million (ppm).

IV. RESULTS AND DISCUSSION

A. Proximate Analysis of Coal Quality

The results of the proximate analysis indicate variations in the quality of the coal samples. The proximate analysis results are presented in the following Table 1 and Table 2.

Table 1. Proximate Analysis Sample KS100

Testing Parameter	AR	Adb	Unit
Total Moisture	26.09	-	%
Inherent Moisture	-	12.14	%
Volatile Matter	26.25	31.20	%
Ash Content	24.11	28.66	%
Ficed Carbon	23.55	27.99	%
Sulfur Content	2.56	3.04	%
Calorie Value	3560	4233	Kcal/Kg

Table 2. Proximate Analysis Sample KS300

Testing Parameter	AR	Adb	Unit
Total Moisture	36.09	-	%
Inherent Moisture	-	14.77	%
Volatile Matter	31.48	34.93	%
Ash Content	10.36	11.50	%
Ficed Carbon	34.97	38.80	%
Sulfur Content	1.42	1.58	%
Calorie Value	4866	5400	Kcal/Kg

The proximate analysis results of samples KS100 and KS300 demonstrate contrasting characteristics in their fundamental compositions, despite their shared regional origin. Sample KS300 exhibits a higher Total Moisture (TM) content of 36.09% (AR) compared to 26.09% (AR) in KS100, yet the most significant divergence is observed in the inorganic mineral constituents. Sample KS100 is characterized by a substantially high ash yield of 24.11% (AR) and a sulfur content of 2.56% (AR), whereas KS300 maintains a much lower ash content of 10.36% (AR) and sulfur at 1.42% (AR).

These variations in mineral matter directly dictate the thermal performance of the coal, as the high concentration of inorganic impurities in KS100 acts as a diluent that significantly reduces its combustible

potential. Consequently, the Calorific Value (CV) of KS100 is limited to 3,560 kcal/kg (AR), while the lower inorganic content in KS300 allows for a higher energy output of 4,866 kcal/kg (AR). This significant presence of inorganic material in KS100, reflected in its high ash yield, not only suppresses the heating value but also indicates a substantial accumulation of non-combustible mineral phases that may serve as a host for specific trace elements.

B. Rare Earth Elements Concentration

The concentrations of rare earth elements (REEs) were determined through Inductively Coupled Plasma (ICP) analysis. The ICP testing conducted on samples KS100 and KS300 confirms the presence of various rare earth elements, as detailed in the following Table 3.

Table 3. Rare Earth Elements Analysis

No	Code	Parameter	Grade	Unit
1	KS100	<i>Cerium (Ce)</i>	114	Ppm
		<i>Lanthanum (La)</i>	60.5	
		<i>Neodimium (Nd)</i>	50.51	
		<i>Praseodimium (Pr)</i>	14.07	
		<i>Europium (Eu)</i>	1.85	
		<i>Gadolinium (Gd)</i>	16.03	
		<i>Samarium (Sm)</i>	4.43	
		<i>Disprosium (Dy)</i>	7.82	
		<i>Scandium (Sc)</i>	16.23	
		<i>Ytrium (Y)</i>	44.13	
		Total	329.57	
2	KS300	<i>Cerium (Ce)</i>	150	Ppm
		<i>Lanthanum (La)</i>	67.24	
		<i>Neodimium (Nd)</i>	91.76	
		<i>Praseodimium (Pr)</i>	16.54	
		<i>Europium (Eu)</i>	3.46	
		<i>Gadolinium (Gd)</i>	35.54	
		<i>Samarium (Sm)</i>	9.9	
		<i>Disprosium (Dy)</i>	14.46	
		<i>Scandium (Sc)</i>	35.54	
		<i>Ytrium (Y)</i>	68.86	
		Total	493.3	

The ICP analysis results confirm the presence of a diverse suite of Rare Earth Elements (REEs) in both coal samples, with concentrations showing a heterogeneous geochemical distribution. Sample KS300 exhibits a more pronounced REEs enrichment compared to KS100, despite having a lower overall ash yield. Cerium (Ce) and Lanthanum (La) emerge as the most dominant light rare earth elements (LREEs) in both samples, with Ce reaching 114 ppm in KS100 and 150 ppm in KS300. However, the most notable finding lies in the concentration of high value elements, specifically Neodymium (Nd), Praseodymium (Pr), and Dysprosium (Dy) which are essential for the production of high-performance permanent magnets used in Electric Vehicle (EV) motors.

Table 4. Rare Earth Elements in Parting

No	Code	Parameter	Grade	Satuan
1	Parting	<i>Cerium (Ce)</i>	65,68	Ppm
		<i>Europium (Eu)</i>	0,010	
		<i>Gadolinium (Gd)</i>	4,92	
		<i>Lanthanum (La)</i>	30,59	
		<i>Neodimium (Nd)</i>	38,91	
		<i>Praseodimium (Pr)</i>	11,34	
		<i>Scandium (Sc)</i>	9,48	
		<i>Samarium (Sm)</i>	3,50	
		<i>Disprosium (Dy)</i>	3,44	
		<i>Ytrium (Y)</i>	12,15	
		Total	180,01	

Sample KS300 demonstrates favorable concentrations for Neodymium at 91.76 ppm, which is nearly double the 50.51 ppm found in KS100. A similar trend is observed for Dysprosium and Praseodymium, where KS300 consistently exceeds KS100 with values of 14.46 ppm and 16.54 ppm, respectively. Furthermore, the Ytrium (Y) content in KS300 reaches 68.86 ppm, indicating a more extensive enrichment of heavy-group elements compared to KS100. These results suggest that the REEs enrichment in these samples is not merely a function of total inorganic volume, but may also be influenced by the mineralogical composition of the ash.

The REEs concentrations in the coal samples were further compared with the results from the parting material (Table 4) to determine the distribution of trace elements across different lithological units. Analytical data from the parting sample shows a total REEs concentration of 180.01 ppm, which is notably lower than the cumulative concentrations found in the coal samples, particularly KS300. Specifically, the Neodymium (Nd) and Dysprosium (Dy) levels in the parting material are recorded at 38.91 ppm and 3.44 ppm respectively, values that are substantially lower than those observed in both KS100 and KS300.

This trend suggests that the REEs enrichment in this deposit is not predominantly hosted within the macroscopic parting layers, but is instead more concentrated within the inorganic matter dispersed inside the coal seams themselves. The lower REEs values in the parting material, compared to the coal-hosted ash, may indicate different mineralogical sources or varying depositional environments during the accumulation of terrigenous sediments. These findings imply that the coal-ash residues from KS300 and KS100 possess higher potential as a source for critical metal recovery than the interbedded parting layers, further emphasizing the importance of specific coal-seam selection for REEs extraction.

The analytical results reveal a compelling trend where REEs enrichment does not necessarily correlate linearly with the degradation of calorific value. According to Dai et al. (2012) [12], REEs accumulation is governed by a complex synergy of geological factors, including peat-forming conditions, diagenetic processes, mineral interactions, tectonic activity, and hydrological regimes. Both KS100 and KS300 originate from the Sinamar Formation, characterized by a lithological assemblage of shale, claystone, and sandstone deposited within a fluvial-deltaic environment [13]. This specific depositional setting plays a fundamental role in determining the trace element characteristics of the coal seams.

The stratigraphic positioning provides further insight into the concentration variance; As illustrated in the stratigraphic column in Figure 5, both the upper and lower boundaries of the investigated coal seam are vertically in direct contact with adjacent claystone layers. Therefore, the higher REEs concentration observed in KS300 compared to KS100 cannot be attributed to differing lithological contacts, but rather to the geochemical dynamics at these boundaries. The interaction between these distinct lithological boundaries suggests a potential correlation with the REE distribution, particularly regarding the hypothetical role of clay minerals. Clay minerals,

primarily composed of alumina (Al_2O_3), can exhibit significant alkali characteristics. Research by Dai et al. (2011) [14] indicates that alkalic tonsteins are typically enriched in Nb, Ta, Zr, Hf, REEs, and Ga, in contrast to silicic tonsteins which yield lower REEs concentrations.

The claystone layers, which are typically characterized by clay minerals rich in alumina (Al_2O_3), potentially possess high adsorption capacities due to their fine-grained structure and negative surface charges. In this framework, the elevated REEs content in the lower layer (KS300) could be influenced by downward leaching processes. Meteoric water or groundwater moving through the overlying strata could potentially leach REEs ions from the upper sections and transport them downward, where they might become trapped and bound by the adsorptive clay minerals at the lower boundary of the coal matrix. This continuous accumulation mechanism offers a plausible explanation for why the lower section (KS300) exhibits a higher REEs enrichment compared to the upper section (KS100).

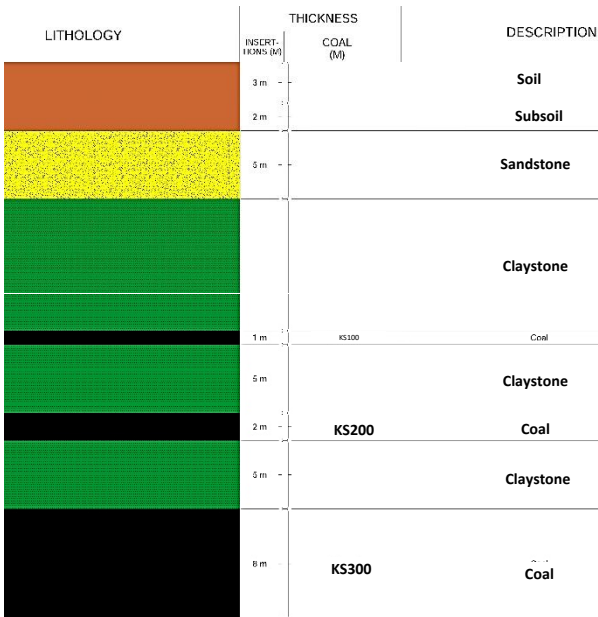


Figure 5. Stratigraphy of Coal Seam

These results provide new insights into the potential of higher-quality coal, such as sample KS300, which exhibits higher REEs concentrations compared to KS100 due to specific geological conditions and interactions with the surrounding strata. These findings could serve as a strategic guide for further REEs exploration within coal deposits.

However, despite the detection of REEs, the current concentrations within the raw coal remain below the threshold for economic viability. According to Joshi et al. (2013) [15], the minimum REEs concentration in coal ash required for feasible industrial processing is 500 ppm. Furthermore, Jegal et al. (2015) [16] noted that several global coal basins possess REEs concentrations exceeding 1,000 ppm, such as the Rettikhovka deposit in Russia (1,141 ppm), the Songzao basin in China (2,446 ppm), and the Aduunchuluun deposit in Mongolia, which reaches up to 5,178 ppm.

Despite these challenges, REEs enrichment typically occurs within the fly ash (coal combustion residuals), and further concentration can be achieved through mineral processing techniques. Beneficiation methods, such as shaking table density separation, have been proven effective in increasing REEs grades [17]. Therefore, while the raw coal concentrations are modest, the potential for REEs recovery lies in the processing of combustion by-products and the implementation of advanced physical separation methods.

Seredin and Dai (2012) [18] classify REEs enrichment into three genetic types: Type L (associated with tuffaceous or clastic sediments), Type M (derived from acidic groundwater circulation), and Type H (influenced by alkali-rich fluids or volcanic activities). In the context of the South Sumatra Basin, specifically at the Air Laya mine, REEs enrichment is predominantly identified as Type H, which is heavily influenced by the hydrogeological cycles within the coal basin [14]. However, no evidence of hydrothermal activity influencing the study area has been identified thus far. Consequently, further investigation is required to definitively categorize the REEs enrichment type at this specific location, particularly to distinguish between authigenic, syngenetic, or potential epigenetic influences that may have shaped the geochemical profile of the coal seams.

V. CONCLUSION

This research demonstrates that the occurrence of Rare Earth Elements (REEs) within the studied coal seams is not directly correlated with either calorific value reduction or the total volume of inorganic matter. Although sample KS100 possesses a higher ash yield (24.11%) compared to KS300 (10.36%), the concentrations of REEs, particularly critical elements for permanent magnet production such as Neodymium (91.76 ppm) and Dysprosium

(14.46 ppm) are notably more pronounced in sample KS300. Furthermore, comparative analysis reveals that REEs concentrations are more concentrated within the inorganic matter dispersed inside the coal seams rather than in the macroscopic parting layers.

These findings suggest that REEs enrichment is likely influenced by specific geological settings and the mineralogical composition of the ash rather than the absolute quantity of impurities. The position within the stratigraphic sequence and the dynamics at the lithological boundaries with adjacent claystone layers are suspected to play a role in the accumulation of these elements, potentially due to the hypothetical adsorption characteristics associated with clay minerals. While the concentrations in the raw coal remain below the 500 ppm economic threshold, the enrichment observed in the inorganic fraction, especially in higher-quality coal seams, underscores the potential of coal-fired combustion by-products as a strategic alternative feedstock. Consequently, this study provides a framework for targeted REEs exploration by prioritizing coal seams with specific geological and mineralogical characteristics.

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