Predicting Critical Elements in Coal Mine Waste: A Machine Learning and Spatial Statistics Approach for a Low-Emission Future

MONASH University

MONASH
BUSINESS
SCHOOL

Department of Econometrics & Business Statistics

📞 (03) 9905 2478
✉ BusEco-Econometrics@monash.edu

ABN: 12 377 614 012

Yuhao Long
Master of Business Analytics
33412448
ylon0012@student.monash.edu

Evan Ginting
Master of Business Analytics
33477558
egin0003@student.monash.edu

Report for
ETC5543

27 September 2024

Contents

Abstract

Background and Motivation

Critical elements overview

In this technology advancement era where mineral-based technologies are relied by many industrial sectors, critical elements become highly-sought elements in the world (Emsbo, Lawley, and Czarnota 2021). Critical elements can be defined by two main criteria: first, elements that are essential for manufacturing modern technologies, supporting economic frameworks, and ensuring national security; and second, elements with vulnerable supply chains, which can be affected by political issues, geographic concentration of extraction or production, and natural disasters (Sinclair and Coe 2024-04; Fortier et al. 2018; DISR 2023).

According to Critical Minerals Strategy 2023–2030 (Geoscience Australia 2023), Geoscience Australia has identified 15 elements as highly vulnerable to future supply chain disruptions and additional 15 elements as moderate risk, which defined in Table 1 (Coyne and Campbell 2023; Skirrow et al. 2013; IEA 2024a; Fortier et al. 2018; Austrade 2024). Among these critical elements, Rare Earth Elements (REE) represent a significant subset. REEs are a group of 17 chemically similar metallic elements composed of fifteen lanthanides, scandium, and yttrium. They further grouped into light (LREEs) and heavy (HREEs) based on their atomic number, electron arrangement, and chemical properties (Reid 2018). Ultimately, critical elements (including REE) are crucial for many high-tech industries, including electronics, renewable energy, and defense (Huang, Fan, and Tiand 2018).

Global initiatives to reduce carbon emissions by transitioning to clean energy have led to increasing demand for critical elements, which are essential resources for achieving this goal (IEA 2021; Wang et al. 2022). According to IEA (2024b) research, demand for these elements is projected to double, triple, or even quadruple, depending on the scenario, relative to current production levels. Among these elements, lithium is experiencing the most rapid growth due to rising demand for electric vehicle (EV) batteries, while copper leads in terms of production volume. Graphite demand is expected to almost quadruple, and the demand for nickel, cobalt, and rare earth elements (REEs) is projected to double. Furthermore, Fortier et al. (2018) indicates that the growing reliance on critical elements is also driven by their applications across various key sectors, including energy, defense, communications, healthcare, transportation, and agriculture. These dynamics have intensified competition to discover new sources and establish stable, long-term supply chains for these vital resources (Emsbo, Lawley, and Czarnota 2021). The prominent usage of each element and its projected demand are also detailed in Table 1.

Table 1: *Summary of Critical Elements: Production, Global Share, Projected Demand, and Usage*

Critical Element	Production (Kilotonnes) [1]	Global Production (Percentage)	Projected Demand (Kilotonnes) [2]	Usage [3]	Level
Aluminum and derivative (Al)	20	14	-	Aerospace alloys, Coating in Li-ion batteries	High
Cobalt (Co)	5.9	3	243.03	Li-ion battery cathodes, stainless steels, superalloys	High
Gallium (Ga)	-	-	0.25	Radar, light-emitting diodes (LEDs), photovoltaics films	High
Germanium (Ge)	-	-	0.03	Fiber/infrared optics, Polymerization Catalysts, semiconductors	High
Lithium(Li)	61	47	615.55	Li-ion batteries, aerospace alloys, ceramics	High
Magnesium(Mg)	2.6	10	30.95	Pyrotechnics, nanocomposites in automotive/aerospace	High
Manganese(Mn)	3.3	17	855	Steel, Agricultural fertilizer, lightweight alloys	High
Nickel(Ni)	150[a]	4.5	2792.68	Cathodes of Li-ion batteries, Non-ferrous alloys	High
Rare-earth elements (REE)[b]	18	6	61.96	Catalysts, magnets, guidance, lasers	High
Silicon (Si)	0.05	1	2025	Solar PVs, Silicon wafers in electronic and photovoltaic cells	High
Tantalum (Ta)	0.057	3	0.44	Micro-capacitors, superalloys	High
Titanium (Ti)	0.85	8.4	22.69	Aerospace and marine alloys, pigment	High
Tungsten (W)	-	-	0.17	Lightning, Cutting and drilling tools, catalysts	High
Vanadium (V)	-	-	35.23	Steel or aerospace alloys	High
Zirconium (Zr)	0.5	36	11.14	Cladding fuel rods, nuclear reactors	High
Antimony (Sb)	4	4	-	Flame retardant, lead-acid batteries	Moderate
Arsenic (As)	-	-	0.55	Microwave communications, pesticides, semiconductors	Moderate
Beryllium (Be)	-	-	-	Satellite communications, lightweight alloys	Moderate

Table 1: *Summary of Critical Elements: Production, Global Share, Projected Demand, and Usage (continued)*

Critical Element	Production (Kilotonnes) [1]	Global Production (Percentage)	Projected Demand (Kilotonnes) [2]	Usage [3]	Level
Bismuth (Bi)	-	-	-	Pharmaceuticals, lead-free solders, cosmetics	Moderate
Chromium (Cr)	66.1	0.3	823.7	Steel or aerospace alloys, leather tanning	Moderate
Fluorine (F)	-	-	-	Refrigerants, dental care, nuclear processing	Moderate
Graphite (Gr)	-	-	8406.7	Rechargeable batteries, semiconductors and sensors, water filtration	Moderate
Hafnium (Hf)	-	-	0.02	Nuclear reactors, aerospace alloys	Moderate
Indium (In)	-	-	0.17	Flat-panel displays, low-Melting Alloys, semiconductors	Moderate
Molybdenum (Mo)	-	-	104.44	Improving strength and corrosion resistance in steel alloys	Moderate
Niobium (Nb)	-	-	1.97	High-Strength Low-Alloy (HSLA) Steel, superalloys, superconductors, welding	Moderate
Platinum-group elements (PGE)[c]	<0.01	<0.01	0.03	Catalysts, jewelry, thermocouples	Moderate
Rhenium (Re)	-	-	-	Superalloys, catalysts, electrical Contacts, filaments	Moderate
Selenium(Se)	-	-	0.26	Alloying agents, solar cells, glass production	Moderate
Tellurium (Te)	-	-	1.55	Copper or steel alloys, semiconductors, solar cells, thermoelectric Materials	Moderate

[a] Data collected in 2012.

[b] 17 elements, including lanthanoid, Scandium (Sc), and Yttrium (Y).

[c] 6 elements, including all transition metals in the d-block.

Source: [1] Skirrow et al., 2013 & Coyne and Campbell, 2023; [2] IEA, 2024b; [3] Fortier et. al., 2018; Austrade, 2024

As one of the promising top global producers of these critical elements, Australia, with its abundant deposit and technological expertise, plays a pivotal role in the sustainable energy transition and supply chain stability. Australia is the largest producer of lithium, the third largest producer of cobalt, and the fourth largest producer of rare earths. It also produces significant amounts of aluminium,

nickel, and copper, which are essential for low-emission technologies like electric vehicles, solar panels, and wind turbines (DISR 2023). Australia's Government strategy to ensure the fulfillment of this potential has been proactive and multifaceted, especially in the past 5 years. The strategy include a range of incentives, finance facilities, grants and other support for the critical elements sector. Some of the important initiatives as reported in DISR (2023), are:

1). The Australian Government's Critical Minerals Facility, with AUD 4 billion budget, supports projects that are aligned with the nation's Critical Minerals Strategy and serve the national interest.

2). The Northern Australia Infrastructure Facility (NAIF) allocates up to AUD 500 million of the AUD 5 billion to help finance projects in the Northern Territory, Queensland, and Western Australia.

3). The Junior Minerals Exploration Incentive (JMEI) promotes investment in small minerals-exploration firms that focus on greenfield exploration.

4). Australian federal, state and territory government authorities are collaborating on the AUD 10 million Critical Minerals National Productivity Initiative to develop pre-feasibility studies of common-user infrastructure for the critical elements sector.

5). The Major Projects Facilitation Agency (MPFA) supports developers of projects over AUD 20 million by providing information on Australian Government regulations and approvals, mapping out critical approval processes, and communicating with regulators to address issues.

6). The Critical Minerals Production Tax Incentive offers a production incentive worth 10 percent of relevant processing and refining costs for Australia's 31 critical elements. This incentive is available for up to 10 years per project for production between 2027–28 and 2039–40, provided the projects reach final investment decisions by 2030.

Critical elements in coals

The green technology initiatives and commitments by countries worldwide for decarbonization have led to a growing market of clean energy and technology. As a result, critical elements, including REE, are projected to be in high demand in the future (United States Department of Energy 2017). Currently, China leads the world in REE production, dominating the international trade and global value chain of rare earths (USGS 2024). However, their recent export restrictions on REE have led to a disruption in the global supply chain (Mancheri 2015). In response, there is an increasing focus on identifying alternative sources of critical elements, with coal being explored as a potential new source of critical elements (Hodgkinson and Grigorescu 2021).

In Hodgkinson and Grigorescu (2020) element mapping project on Bowen basin Table 2, the largest coal reserves in Australia, the concentration of element composition is subjective to sample's lithology rather than the depth grading:

1). In coal and its derivatives, although the majority of element concentrations fall below the benchmark when compared to Post-Archaean Australian Shales (PAAS) standard (McLennan 2011), a widely used geochemical reference material in the average composition of shales, local samples exhibit enrichment in Heavy Rare Earth Elements (HREEs) and scandium(Sc). Additionally, concentrations of the critical element bismuth (Bi) are abnormally elevated, showing levels 4-6 times higher than the crustal average.

2). Siltstone and mudstone yield unremarkable findings in terms of elemental enrichment, with most element concentrations failing to meet significant thresholds. However, the concentration of cobalt compounds approaches the crustal average, suggesting potential economic value that warrants further investigation.

3). Tuffaceous rock, formed from volcanic ash, is rich in pumice and lithic fragments. Samples reveal elevated concentrations of strategic elements, including Rare Earth Elements (REEs), gallium (Ga), and bismuth (Bi). Moreover, a potential lithium-rich borehole has been identified, with lithium concentrations approximately five times higher than the crustal average.

Table 2: *Summary of Hodginkson's research on critical element mapping in coal mines*

Critical Element	PAAS Standard	Average Concentration (ppm)	Highest Concentration (ppm)	Above Crustal Average (Percentage)
Coal Seam & Associate				
Lithium	21.0	13.7	**25**	22
REE	184.0	115.8	**205**	11
Cobalt	17.0	16.9	**30**	44
Nickel	47.0	11.2	40	0
Tantalum	1.0	0.33	1	33
Vanadium	97.0	85.6	**140**	22
Zirconium	193.0	102.1	160	0
Gallium	17.0	12.3	**25**	44
Bismuth	0.2	**0.59**	**1**	67
Chromium	92.0	14.33	51	0
Niobium	12.0	7.9	**32**	11
Molybdenum	1.0	**1.33**	**3**	78
Siltstone & Mudstone				
Lithium	21.0	17.2	**28**	33
REE	184.0	138.8	**189**	17

Table 2: *Summary of Hodginkson's research on critical element mapping in coal mines (contin-
ued)*

Critical Element	PAAS Standard	Average Concentration (ppm)	Highest Concentration (ppm)	Above Crustal Average (Percentage)
Cobalt	17.0	**39.3**	**134**	67
Nickel	47.0	25.8	**73**	33
Tantalum	1.0	0.2	1	17
Vanadium	97.0	**102**	**225**	33
Zirconium	193.0	116.8	**243**	17
Gallium	17.0	15	**22**	33
Bismuth	0.2	0.18	**0.4**	67
Chromium	92.0	51.33	**266**	17
Niobium	12.0	4.67	8	0
Molybdenum	1.0	0.67	1	67
Tuffaceous Rocks				
Lithium	21.0	**21.5**	**105**	12
REE	184.0	**244**	**441**	88
Cobalt	17.0	9.25	**19**	12
Nickel	47.0	3.75	30	0
Tantalum	1.0	**1.1**	**2**	100
Vanadium	97.0	27.9	70	0
Zirconium	193.0	153.75	**282**	25
Gallium	17.0	**32.25**	**37**	100
Bismuth	0.2	**0.71**	**1.2**	100
Chromium	92.0	0	0	0
Niobium	12.0	9.63	**18**	25
Molybdenum	1.0	1	**5**	50

Source: Adapted from Hodginkson et al., 2020

Economic concentrations

Before the recent surge in demand, extracting critical elements (including REE) from coal was
considered costly, however, methods have been developed that reduce the cost and also enviromentally
friendly. Coal and coal byproducts are substantially enhanced with trace metals and have been
proposed as a potential source (Eterigho-Ikelegbe, Harrar, and Bada 2021). A report by US Department
of Energy suggests that extracting REEs from coal material already mined for other purposes, either as
a dual product or byproduct, could be more cost-effective than a dedicated REE mining. Despite the
challenge of processing large volumes to obtain economic concentrations, cost may be reduced due to
the pre-processed (mined, crushed, and washed) state of the materials and transported to areas with
existing infrastructure (United States Department of Energy 2017; Hodgkinson and Grigorescu 2021).

Based on research, the elements and metals in coal that are considered to have the best chance for economic recovery are: REE, Ag, Au, PGEs, Be, Se, V, Ga, Sb, Sc, Mo, W, Re, Ge, U, Y, Nb, Zr, Al (Dai and Finkelman 2018).

Efficient extraction of critical elements from coal or coal ash, and finding coal sources with highly elevated concentrations of these elements, are essential prerequisites. The value of the element in any coal sources largely determined by their concentration, which varies based on geological and geochemical conditions. Therefore, to economically recovering critical elements from coal is by identifying sources with the highest critical elements levels and accessibility first before proceeding to extraction and recovery stages (Eterigho-Ikelegbe, Harrar, and Bada 2021). Reid (2018) in his report suggests that critical elements average level in coal is typically just 35 ppm, which is insufficient for economic extraction. While Seredin and Dai (2012) in their reports suggests that a cutoff grade for Rare Earth Oxides (ROE) for coal seam has been suggested as 800-900 ppm. Table 3 provide suggested cut-off grade for 18 critical elements. Additionally, Talan and Huang (2022) reports that coal sources are often relatively enriched in the heavy rare earths (HREEs, Ho, Er, Tm, Yb, Lu) and critical rare earths (CREEs, Y, Nd, Dy, Eu, Tb) compared to traditional mineral deposits. A cut-off grade of 115–130 ppm rare earth element on a whole mass basis may be considered economical. However, the U.S. Department of Energy set a criterion in their work assessing raw coal with total rare earth element content greater than 300 ppm on a whole dry coal basis.

Existing economic deposits

Currently, there are no coal mines or coal basins extracting critical elements (including REE) at a commercial states. Most sources found conclude that we are still in the research and development process (Hodgkinson and Grigorescu 2020; Dai and Finkelman 2018; Eterigho-Ikelegbe, Harrar, and Bada 2021; Honaker et al. 2019; Talan and Huang 2022). A report by Eterigho-Ikelegbe, Harrar, and Bada (2021) suggests that the research and development are primarily at the laboratory and pilot scale stages. For example, scholars like Honaker and coworkers who have significant experience in this subject, have constructed a 0.23 t/h solid feed pilot plant for testing different coal-based feedstocks (Honaker et al. 2019). However, commercial-scale extraction processes have not yet been widely implemented. Talan and Huang (2022) report support this finding as well. They propose a potential approach for commercial-scale extraction of critical elements, indicating ongoing effort to bridge the gap between laboratory research and commercial application. Additionally, they note that further validation and techno-economic analysis are required before these processes can be scaled up commercially. Furthermore, scholars who focusing their research on China's coal resources also suggest further research is needed to scale up the extraction process (Qin et al. 2015b,a; Liu et al. 2024; Zhao et al. 2019; Zou et al. 2023). Given that China is the leader in critical elements

Table 3: *Selected critical elements with their suggested cut-off grade (ppm)*

Critical Element	Suggested Cut-off Grade
U	1000
Ge	300
V	1000
Se	500–800
Ga	100 (50)
REE	1000
Y	300
Sc	100
Nb	300
Zr	2000
Mo	1000
Re	1
Wi	1000
Au + Pt + Pd	2
Ag	10
Be	300
Sb	1000
Cs	150

Source: Adapted from Dai and Finkelman, 2018

production, this fact indicates that their production of critical elements does not primarily come from coal and its byproducts.

We can conclude that significant research and development efforts have been made towards commercial extraction of critical elements from coal and coal byproducts. However, it is still long way from actual large-scale implementation. Most scholars indicate the necessity of considering sustainability factors. Effective waste management and treatment, along with the evaluation of extraction costs and technical feasibility, are important. At the end of the day, these elements are going to be utilised in green technology initiatives, such as renewable energy systems and electric vehicles, which demand high-purity materials. Ensuring that their extraction processes are environmentally and economically sustainable is crucial to align with the goals of these green technologies initiatives. Furthermore, ongoing research is vital to bridge existing technology gaps and develop robust, scalable methods that can transition from pilot projects to commercial operations.

Extraction of critical elements

There are several stages required for critical elements can be extracted from coal and coal byproducts. Coal and coal byproducts is first prepared by crushing and milling to release the organic from inorganic elements to generate fine concentrates. These concentrates are then undergo further separation techniques such as physical (froth flotation, electrostatic, magnetic, gravity) and chemical (leaching).

Later, it will further processed into purification to extract the REE into pure oxide form (e.g. REO). REO can be standalone products, however, market demand dictates their conversion into metals. Thus, in the refining stage, using an electrolysis or a metallothermic reduction process, REOs will be converted into high-purity rare earth metals. These metals may then be alloyed with other elements to make them harder and stronger for the end-use market (Eterigho-Ikelegbe, Harrar, and Bada 2021; United States Department of Energy 2017; Talan and Huang 2022). The figure 1 visualise this process.
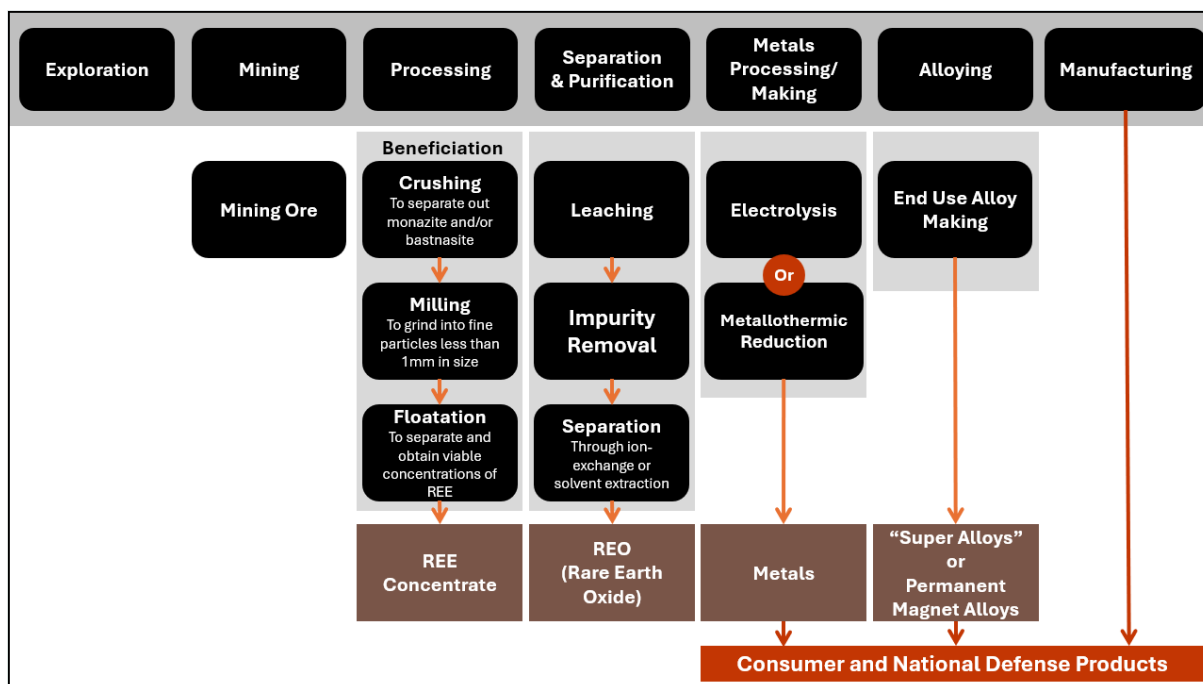

Figure 1: *REE Value Chain (Source: US Department of Energy, 2017)*

Recently, water-leaching is a prevailing approach since it mitigate the flaw from traditional techniques. Water leaching can be considered as less environmentally detrimental compared to strong acid/alkaline leaching, as well as cost effective for solvent selection. The crucial stages on this preparation workflow are low temperature activation and water leaching. During the stage of low temperature activation, the chemical reaction within coal fly ash (CFA) will be facilitated by complexation agents (ammonium salts or weak acids) in covered alumina crucibles, which help liberate critical elements from the matrix of the CFA. After the activation and cool down to ambient temperature, the tablets are placed in water for the leaching and dissolve process. Water acts as the leaching solvent, extracting these soluble elements into the leachate.The configuration in temperature and mass ratio of solvent will be the vital determinant for optimized recovery. Take Lithium example, it can achieve a stable leaching efficiency of 90% through ammonium fluoride leaching at 150°C with a SiO_2/NH_4F mass ratio of 1:1.35 Xu et al. (2021).

Another innovation is Hydrophobic-Hydrophilic Separation (HHS), designed to leverages the disparity of affinity (water-repellent & water-friendly) properties of substances to achieve separation.It can treat as a complementary application for small particle delamination without size limit, providing flexible and extensible purpose in the segregation of ultrafine coal Hodgkinson and Grigorescu (2021).

In precious Hodgkinson and Grigorescu (2020) element mapping project on Bowen basin,the largest coal reserves in Australia, the concentration of element composition is subjective to sample's lithology rather than the depth grading:

1). In coal and derivative, albeit majority of element concentrations is inferior of the benchmark against earth crust average, local samples exhibit enrichment in HREE and Scandium in respect to McLennan (2011) Post-Archaean Australian Shales (PAAS) standard , while abnormal 4-6 times higher than crustal average in moderate critical element, Bismuth(Bi) .

2). Siltstone and mudstone has a lackluster finding to classify enrichment for majority of elements concentration,except for the concentration of Cobalt compound barely meet crustal average, whose ubiquitous economic value may warrant further examination.

3). As the sediment from volcanic ash, tuffaceous rock is rich in pumice and lithic fragments. The sample display a series of elevated concentrations of strategic elements including REE, Ga and Bi. Besides, a potential Lithium-rich borehole is found, with approximate 5 times higher than crustal average.

Objectives and Significance

The primary objective of this study is to develop a predictive model using machine learning and spatial statistics to identify and quantify critical minerals—such as copper, lithium, nickel, cobalt, and rare earth elements—in coal mine waste. By analyzing existing coal data, this study aims to provide valuable insights into the potential recovery of these essential minerals from coal deposits, contributing to waste reduction and supporting the transition to low-emission technologies. The outcome of this study will help assess the economic value of these minerals and promote sustainable practices within the mining and energy sectors.

The study utilises multiple datasets, some of which are publicly available while others are confidential. The public dataset was released by the Australian Coal Industry's Research Program (ACARP) in 2021, whereas the confidential data comes from Matrix Geoscience's clients. Although the datasets originate from different sources, both contain information on the concentration of various critical elements sampled from coal mines and power plants across Australia. Additionally, the study employs data on elemental concentrations from Post Archean Australian Shale (PAAS), which represents the

background crustal abundance of elements. This comparison helps determine whether the elemental concentrations in the coal samples exceed typical crustal abundance levels.

This study is significant because it addresses a critical gap in understanding the presence and potential recovery of valuable minerals from coal mine waste. By employing advanced machine learning and spatial statistics techniques, the project has the potential to revolutionise how the mining industry views coal waste—transforming it from an environmental challenge into a resource opportunity. The findings could contribute to more sustainable mining practices, reduce waste, and support the global transition to low-emission technologies by securing a local supply of critical minerals. Furthermore, this research could pave the way for further exploration of coal mine waste as a valuable resource in other regions, creating economic and environmental benefits on a broader scale.

Data

Data source and description

Data cleaning

Exploratory Data Analysis

The Exploratory Data Analysis (EDA) was carried out on critical elements concentration data, which provide information about the concentration of critical mineral across different areas in Australia that has been normalised using PAAS (Post-Archean Australian Shale) standard. The primary objective of this analysis is to gain a deeper understanding of the data's structure and key characteristics. Through this, we aim to identify significant trends, correlations, and outliers that may influence the outcomes of the study.

The EDA for critical elements concentration data starts with a descriptive statistics for every critical elements included in the data. These summary statistics can be found in the Table 4. The descriptive statistics features include the minimum value of the critical elements, maximum value, the mean, the median, the standard deviation, and the kurtosis of the variable.

Table 4: *Descriptive Statistics of Elements' Normalised Value*

Element Symbol	Element Description	min	max	mean	median	sd	kurtosis
Ag	Silver	2.000	13.200	4.142	3.600	2.389	5.783
Al	Aluminium	0.000	8.500	0.845	0.438	0.982	34.192
Au	Gold	0.556	12.222	3.521	3.333	2.064	7.764
Ba	Barium	0.013	18.182	1.108	0.750	2.027	43.446
Be	Beryllium	0.033	6.000	1.126	0.667	1.134	7.156

Table 4: *Descriptive Statistics of Elements' Normalised Value* (continued)

Element Symbol	Element Description	min	max	mean	median	sd	kurtosis
Bi	Bismuth	0.787	25.197	3.685	2.402	3.302	17.818
Cd	Cadmium	0.102	7.347	1.271	0.918	1.115	9.839
Ce	Cerium	0.056	5.938	0.956	0.985	0.595	21.060
Co	Cobalt	0.118	7.882	0.906	0.588	1.133	17.661
Cr	Chromium	0.012	10.807	0.441	0.205	1.048	54.642
Cs	Caesium	0.024	6.870	1.068	0.923	0.910	12.858
Cu	Copper	0.040	10.200	1.681	1.880	1.160	13.140
Dy	Dysprosium	0.114	5.286	1.522	1.517	0.847	5.566
Er	Erbium	0.087	4.957	1.401	1.320	0.815	6.383
Eu	Europium	0.114	7.773	1.676	1.648	0.969	8.535
Fe	Iron	0.000	9.689	0.474	0.180	1.066	45.053
Ga	Gallium	0.076	3.076	1.293	1.291	0.684	2.148
Gd	Gadolinium	0.132	6.605	1.589	1.513	0.901	7.420
Ge	Germanium	0.088	43.750	7.481	0.344	13.031	3.653
HREE	Ho+Er+Tm+Yb+Lu	0.036	0.995	0.282	0.267	0.157	6.712
Ho	Holmium	0.125	4.750	1.352	1.306	0.767	5.962
In	Indium	0.400	7.200	1.434	1.000	1.117	9.581
LREE	La+Ce+Pr+Nd+Pm+Sm	0.089	4.214	1.020	1.064	0.540	6.992
La	Lanthanum	0.100	2.540	0.871	0.930	0.480	2.566
Li	Lithium	0.250	14.250	2.386	2.000	1.974	9.533
Lu	Lutetium	0.000	6.250	1.540	1.438	0.919	7.067
MREE	Eu+Gd+Tb+Dy+Y	0.088	4.384	1.361	1.344	0.756	5.952
Mn	Manganese	0.002	18.717	0.594	0.109	1.884	66.528
Mo	Molybdenum	0.067	13.733	2.971	2.667	2.195	10.237
Nb	Niobium	0.042	3.567	0.622	0.647	0.402	16.601
Nd	Neodynium	0.065	4.423	1.145	1.221	0.645	4.693
Ni	Nickel	0.023	8.182	0.386	0.159	0.869	44.099
Pb	Lead	0.052	4.909	1.276	1.235	0.856	6.139
Pr	Praseodymi	0.056	4.704	1.033	1.092	0.596	7.452
REE	La+Ce+Pr+Nd+Sm+Eu+Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu	0.134	4.174	1.089	1.130	0.539	6.574
REEY	La+Ce+Pr+Nd+Sm+Eu+Gd+Tb+Dy+Ho+Er+Tm+Yb+Lu+Y	0.138	3.641	1.120	1.151	0.528	4.600
Rb	Rubidium	0.001	2.670	0.472	0.441	0.396	5.920
Re	Rhenium	0.000	7.500	4.286	5.000	3.134	1.792
Sc	Scandium	0.162	4.985	1.137	1.191	0.610	8.482
Sm	Samarium	0.089	4.689	1.421	1.460	0.785	4.173

Table 4: *Descriptive Statistics of Elements' Normalised Value* (continued)

Element Symbol	Element Description	min	max	mean	median	sd	kurtosis
Sn	Tin	0.182	2.364	0.726	0.655	0.350	6.862
Sr	Strontium	0.006	4.571	0.955	0.916	0.608	6.965
Ta	Thallium	0.133	4.000	0.865	0.920	0.482	14.453
Tb	Terbium	0.156	4.578	1.378	1.359	0.760	5.576
Th	Thorium	0.044	5.329	1.172	1.107	0.853	6.382
Tl	Tantalum	0.030	10.000	1.942	0.715	3.123	5.782
Tm	Thulium	0.303	5.455	1.453	1.364	0.816	7.679
U	Uranium	0.054	4.286	1.289	1.304	0.805	3.219
V	Vanadium	0.019	4.299	1.038	1.103	0.666	5.959
Y	Yttrium	0.045	4.568	1.278	1.250	0.764	6.443
Yb	Ytterbium	0.091	5.409	1.462	1.400	0.854	6.361
Zn	Zinc	0.014	4.324	0.921	0.930	0.699	4.134
Zr	Zirconium	0.021	4.821	0.923	0.979	0.592	9.671

The most important statistics from this table is kurtosis. Kurtosis measures the combined weight of the tails of a distribution relative to its centre. In this way, we can use kurtosis as an indicator of the presence of outliers. A high kurtosis values is indicative of outliers. The summary statistics suggest that Al, Ba, Bi, Ce, Co, Cr, Cs, Cu, Fe, Mn, Nb, and Ni are having many outliers due to high kurtosis value. Validating the outliers will be easier with data visualisation, which will be presented in the next step.

The next step was analysing the distribution of each element's normalised value. By utilising boxplots, it will help identifying the outliers of each critical elements, while also identifying which element's has median value above the PAAS standard. Obtaining these information will help to understand whether certain element is naturally abundance in the nature, thus it is most likely economically efficient to extract. The figure 2 provide these informations.

The boxplots shows some critical points that can be summarised as follow:

- Medians: Most of the elements have their medians close to 0, indicating that the majority of the values are low or concentrated around a lower range. Considering that the threshold to define whether a sample is below/above background is 1 (vertical red dashed line), some elements that have median above the threshold are Re, Ag, Au, Mo, Bi, Li, Cu, Eu, Dy, Gd, Sm, Lu, Yb, Tm, Tb, MREE, Er, Ho, U, Ga, Y, Pb, Nd, Sc, REEY, REE, Th, V, Pr, LREE
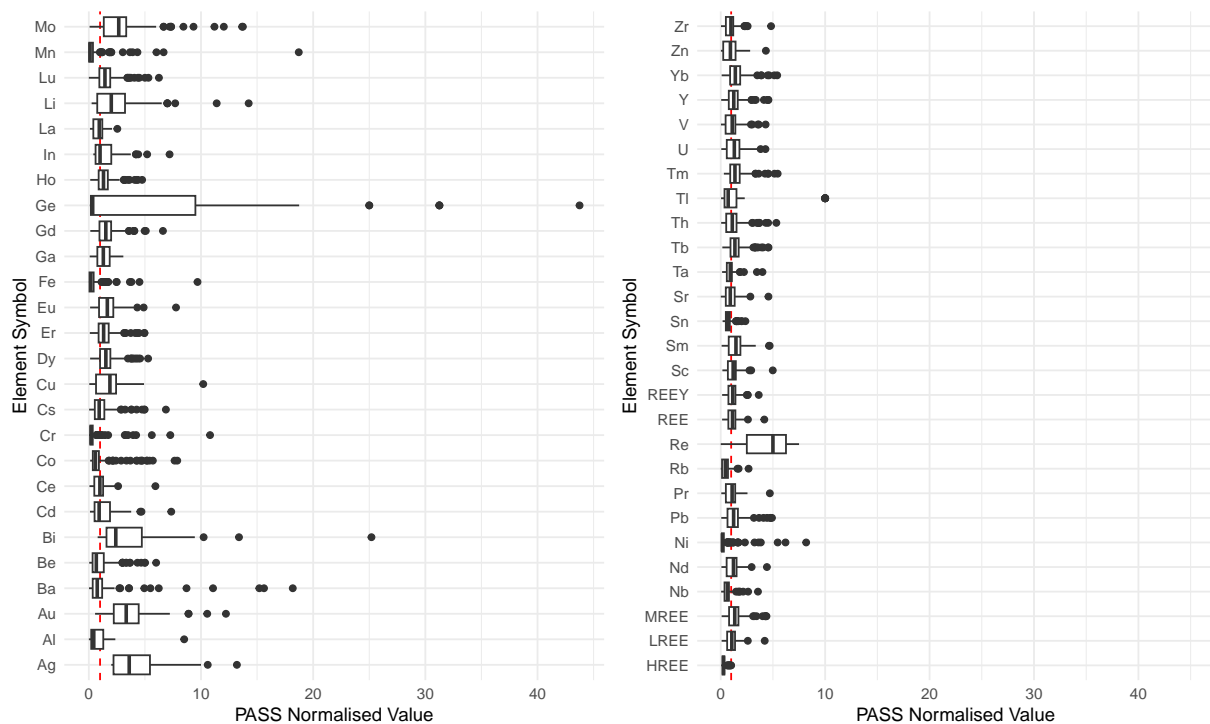
Figure 2: *Distribution of Critical Elements (Box-Plot)*

- Spread and Variability: The elements exhibit varying degrees of spread. For example, Ge shows a wide range with its box stretching from a low value near 0 to a higher value around 10, indicating a large variability. On the opposite side, elements like Mn, Fe, Cr, Co, Rb, Ni, HREE have very narrow IQR, indicating less variability.

- Outliers: Several elements have significant outliers, as indicated by the dots outside the whiskers of the box plots. For instance, Ge, Bi, Mn, and Ba show notable outliers far from the main data range. Additionally, some elements that was reported from table 4, which have high kurtosis are Al, Ba, Bi, Ce, Co, Cr, Cs, Cu, Fe, Mn, Nb, and Ni. These outliers suggest the presence of some unusually high or low values for these elements, which could be of interest for further investigation.

- Symmetry and Skewness: Some elements like Ge, Bi, and Ag appear to have a right skew, with longer whiskers or outliers extending to the right, indicating that the distribution of their normalised values has a tail on the higher end. Elements like Ga and Sm show a more symmetrical distribution with whiskers extending fairly equally on both sides of the box.

- Comparison Accross Elements: Ge stands out with a particularly large spread and median, making it an outlier among the elements. Conversely, many rare earth elements (REE, REEY, MREE, LREE, HREE) have relatively low medians and a small spread, indicating that their normalised values are generally low and clustered.

17

Reference

Austrade (2024). *Australian Critical Minerals Prospectus*. https://international.austrade.gov.au/en/news-and-analysis/publications-and-reports/critical-minerals-prospectus.

Coyne, J and H Campbell (2023). Developing Australia's Critical Minerals and Rare Earths: Implementing the Outcomes from the 2023 Darwin Dialogue.

Dai, S and RB Finkelman (2018). Coal as a promising source of critical elements: Progress and future prospects. *International Journal of Coal Geology* **186**, 155–164.

DISR (2023). *Critical Minerals Strategy 2023–2030*. https://www.industry.gov.au/publications/critical-minerals-strategy-2023-2030.

Emsbo, P, C Lawley, and K Czarnota (2021). Geological surveys unite to improve critical mineral security.

Eterigho-Ikelegbe, O, H Harrar, and S Bada (2021). *Rare earth elements from coal and coal discard – A review*.

Fortier, S, N Nassar, G Lederer, J Brainard, J Gambogi, and E McCullough (2018). Draft critical mineral list—Summary of methodology and background information—U.S. Geological Survey technical input document in response to Secretarial Order No. 3359.

Geoscience Australia (2023). Critical Minerals Strategy 2023–2030, 8–14.

Hodgkinson, JH and M Grigorescu (2020). Strategic elements in the Fort Cooper Coal Measures: potential rare earth elements and other multi-product targets. *Australian Journal of Earth Sciences* **67** (3), 305–319.

Hodgkinson, JH and M Grigorescu (2021). *C29030 ACARP - Mapping of Elemental Coal Content for Exploration and Mining*.

Honaker, RQ, W Zhang, J Werner, A Noble, GH Luttrell, and RH Yoon (2019). Enhancement of a Process Flowsheet for Recovering and Concentrating Critical Materials from Bituminous Coal Sources. *Mining, Metallurgy and Exploration* **37**(1).

Huang, Z, M Fan, and H Tiand (2018). Coal and coal byproducts: A large and developable unconventional resource for critical materials – Rare earth elements. *Journal of Rare Earths* **36** (4), 337–338.

IEA (2021). *The Role of Critical Minerals in Clean Energy Transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

IEA (2024a). *Critical Minerals Data Explorer*. https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.

IEA (2024b). *Global Critical Minerals Outlook 2024*. https://www.iea.org/reports/global-critical-minerals-outlook-2024.

Liu, C, T Zhao, G Wang, and D Chen (2024). A review of China's resources of lithium in coal seams. *Frontiers in Energy Research* **12**.

Mancheri, NA (2015). World trade in rare earths, Chinese export restrictions, and implications. *Resources Policy* **46**, 262–271.

McLennan, SM (2011). Relationships between the Trace Element Composition of Sedimentary Rocks and Upper Continental Crust. *G3* **2**(4).

Qin, S, Y Sun, Y Li, J Wang, C Zhao, and K Gao (2015a). Coal deposits as promising alternative sources for gallium. *Earth-Science Reviews* **150**, 95–101.

Qin, S, C Zhao, Y Li, and Y Zhang (2015b). Review of coal as a promising source of lithium. *International Journal of Oil, Gas and Coal Technology* **9** (2). doi: 10.1504/IJOGCT.2015.067490, 215–229.

Reid, I (2018). *Non-energy uses of coal*. https://www.sustainable-carbon.org/report/non-energy-uses-of-coal-report-ccc291/.

Seredin, VV and S Dai (2012). Coal deposits as potential alternative sources for lanthanides and yttrium. *International Journal of Coal Geology* **94**, 67–93.

Sinclair, L and NM Coe (2024-04). Critical mineral strategies in Australia: Industrial upgrading without environmental or social upgrading. *Resources policy* **91**, 104860.

Skirrow, RG, DL Huston, TP Mernagh, JP Thorne, H Dulfer, and AB Senior (2013). Critical Commodities for a High-Tech World: Australia's Potential to Supply Global Demand.

Talan, D and Q Huang (2022). A review study of rare Earth, Cobalt, Lithium, and Manganese in Coal-based sources and process development for their recovery. *Minerals Engineering* **189**, 107897.

United States Department of Energy (2017). *Report on Rare Earth Elements from Coal and Coal Byproducts*.

USGS (2024). *Mineral Commodity Summaries: Rare Earths*. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-rare-earths.pdf.

Wang, P, WQ Chen, X Cui, J Li, W Li, C Wang, W Cai, and X Geng (2022). Critical mineral constraints in global renewable scenarios under 1.5 °C target. *Environmental Research Letters* **17**(12), 125004.

Xu, H, C Liu, X Mi, Z Wang, J Han, G Zeng, P Liu, Q Guan, H Ji, and S Huang (2021). Extraction of Lithium from Coal Fly Ash by Low-Temperature Ammonium Fluoride Activation-Assisted Leaching. *Separation and Purification Technology* **279**, Article 119757.

Zhao, L, S Dai, VP Nechaev, EV Nechaeva, IT Graham, D French, and J Sun (2019). Enrichment of critical elements (Nb-Ta-Zr-Hf-REE) within coal and host rocks from the Datanhao mine, Daqingshan Coalfield, northern China. *Ore Geology Reviews* **111**.

Zou, J, H Chen, L Zhao, X Wang, H Li, T Li, and H Wang (2023). Enrichment of critical elements (Li-Ga-Nb-Ta-REE-Y) in the coals and host rocks from the Daping Mine, Yudongnan Coalfield, SW China. *Ore Geology Reviews* **152**, 105245.