The present work was submitted to the Faculty of Engineering

Investigation of rare earth elements (REEs) from coal and coal byproducts

Bachelor Thesis

by

Bold Khosbayar

Supervisor 1 / Examiner 1 **Ms. Bayardulam Jamiyansuren**

Supervisor 2 / Examiner 2 **Prof. Dr. Battsengel Baatar**

Ulaanbatar Nalaikh,

14th of May 2023

Statutory Declaration

Khosbayar Bold	15343214492227
Last Name, First Name	Student ID Number

I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Investigation of rare earth elements (REEs) from coal and coal byproducts

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

Place, Date

Signature

Table of Contents

Acknowledgements

I would like to express my deepest gratitude to my supervisors, Professor Dr. Battsengel and Ms. Bayardulam, for their invaluable guidance, advice, and unwavering support throughout my bachelor's thesis study. Their expertise, dedication, and encouragement were instrumental in my academic success.

I am also grateful to Ms. Azjargal for generously sharing her knowledge and expertise with me, and for her invaluable assistance in the GMIT processing laboratory. Her guidance and mentorship were critical to the success of my research.

I would like to extend my heartfelt thanks to sophomore student Narangua for their support and assistance in the laboratory. Their contributions to my research were essential, and I am deeply grateful for their help.

Finally, I would like to thank my family and friends for their unwavering support and encouragement throughout my academic journey. Their love, motivation, and inspiration have been invaluable to me, and I am forever grateful for their presence in my life.

Abstract

The use of coal fly ash (CFA) as a potential secondary source of rare earth elements (REEs) has gained attention of researchers recently due to its high REEs content. The aim of thesis is to investigate conventional physical separation methods, such as particle size analysis, magnetic separation and froth flotation, for the recovery of REEs from fly ash obtained from a commercial coal-powered plant. The amount of rare earth elements (REEs) present in the sample of coal fly ash was measured using a technique called inductively coupled plasma optical emission spectroscopy (ICP-OES). The findings of the quantitative analysis revealed that the total content of REEs in the coal ash was 416.7 parts per million (ppm). Experimental results showed that flotation was effective in improving the recovery and upgrading of REEs depending on the pH condition of the pulp. The highest REEs recovery 71.72% was achieved at pH 12, while the best grade upgrade 456.44 ppm was achieved at pH 10. However, magnetic separation tests showed that most REEs ended up in the tailings. The performance of various beneficiation methods varied significantly in this study. Overall, it was concluded that physical separation methods could be used to recover REEs from coal fly ash before further processing through hydrometallurgical methods. These findings have important implications for the development of sustainable and cost-effective processes for the extraction of REEs from alternative sources, such as coal fly ash.

List of figures

List of Tables

1. Introduction

Coal and coal ash are known to contain a wide range of elements, including some rare earth elements (REEs). REEs are critical components in many high-tech industries, including electronics, magnets, and renewable energy technologies. As global demand for these materials continues to increase, alternative sources of REEs are becoming increasingly important. Coal and coal ash are attractive sources of REEs due to their widespread availability and potential for extraction.

This study investigates the REEs from coal and coal ash from various sources and focuses on the physical beneficiation of REEs from coal fly ash. The coal sample was taken from the Baganuur coal mine, fly ash samples were collected from thermal power station IV, and bottom ash samples were collected from the Baganuur power station.
The thesis will focus on the following activities:

- Physical beneficiation methods
- The distribution and concentration of REEs in coal and coal ash samples
- Determination of the REEs recovery and grade from coal fly ash

This thesis experiment has been carried out physically. The most time-consuming method was the flotation which was a main focusing study and conducted with many different conditions and during the experiment I learned new techniques and skills. However, some experiments have failed due to equipment failure and lack of experience in practical work. The experiment schedule plan is given below in the table.

Task ID	Task Description	Task Duration	Start Date	End Date	3/28/2023	3/29/2023	3/30/2023	3/31/2023	4/1/2023	4/2/2023	4/3/2023	4/4/2023	4/5/2023	4/6/2023	4/7/2023	4/8/2023	4/9/2023	4/10/2023	4/11/2023	4/12/2023	4/13/2023	4/14/2023	4/15/2023	4/16/2023	4/17/2023
1	Sample preparation	1	3/28/2023	3/29/2023																					
2	Particle size analysis	1	3/28/2023	3/29/2023																					
3	Magnetic separation	1	3/29/2023	3/30/2023																					
4	Flotation	7	3/30/23	4/6/23																					
5	Non-magnetic+flotation	1	4/7/2023	4/8/2023																					
6	Laboratory analysis	7	4/9/2023	4/16/2023																					

Scheduled plan
Most time taken

Table 1. Experiment schedule

1.1 Rare earth elements

Rare earth elements (REEs) are a group of 17 chemical elements that have unique magnetic, luminescent, and electrochemical properties. The 17 elements include the 15 lanthanide group elements, scandium, and yttrium. REEs are the essential raw materials that are used in a wide variety of products including electronics, magnets, catalysts, and new advanced technologies. Rare earth minerals including bastnaesite, monazite, xenotime, and fluocerite are the major industrial minerals. [1]

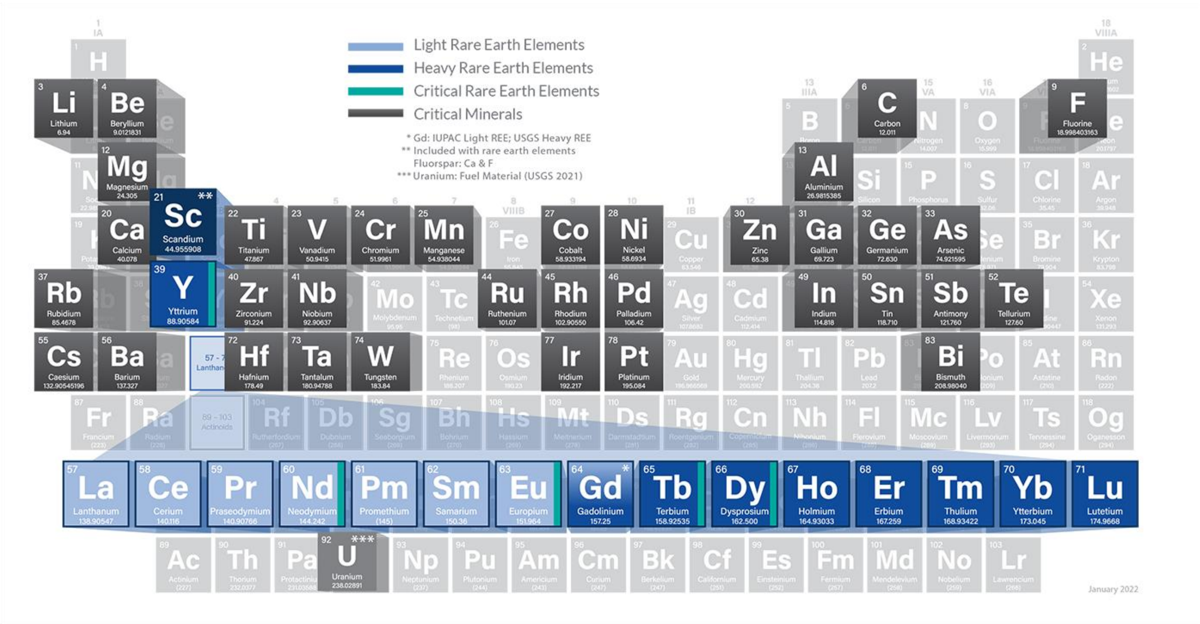


Figure 1. Periodic table of elements

REEs are not actually rare, they are abundant in the earth’s crust, but they can be found in low concentrations in minerals, and extracting these elements from the earth is difficult and expensive so more advanced technologies are needed to extract REEs.

Currently, China is the biggest producer of REEs. In 2009, China, which had a near-monopoly on producing these elements, accounting for 97% of global production, shifted its approach towards the global rare earth market. [1] China introduced export restrictions and taxes to control the global supply and price of these critical materials. As a result, this caused concern among high-tech equipment manufacturers worldwide since numerous advanced applications today heavily rely on rare earth elements, which could have been affected by China's shift in approach towards the global rare earth market. [2] There are many recent studies that are aiming for the potential alternative sources of REEs

Global rare earth reserves amount to 130 million MT

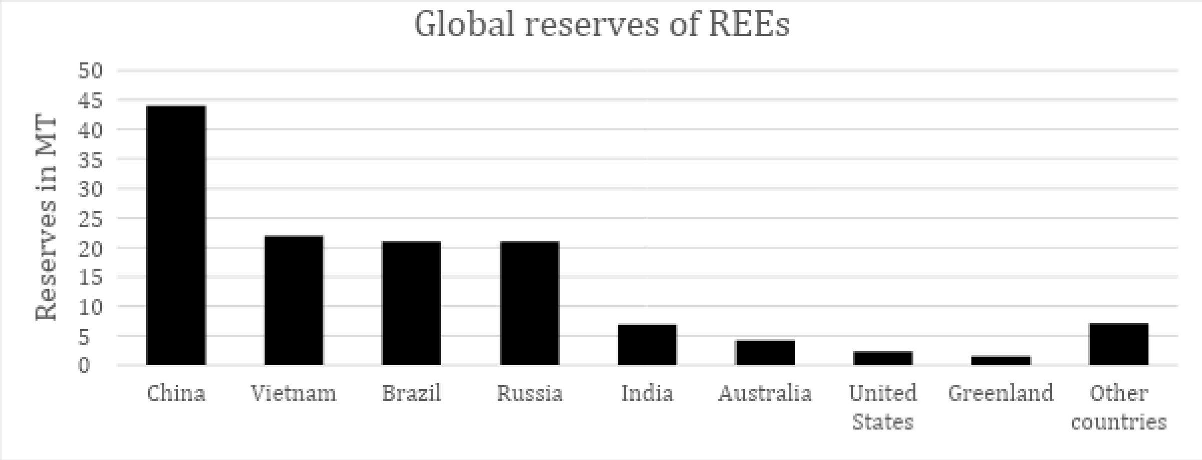


Figure 2. Global reserves

1.1.1 Demand for Rare Earth Elements

Demand for rare earth elements (REEs) has increased in recent years, driven by a growing global population and rapid development of high-tech products.

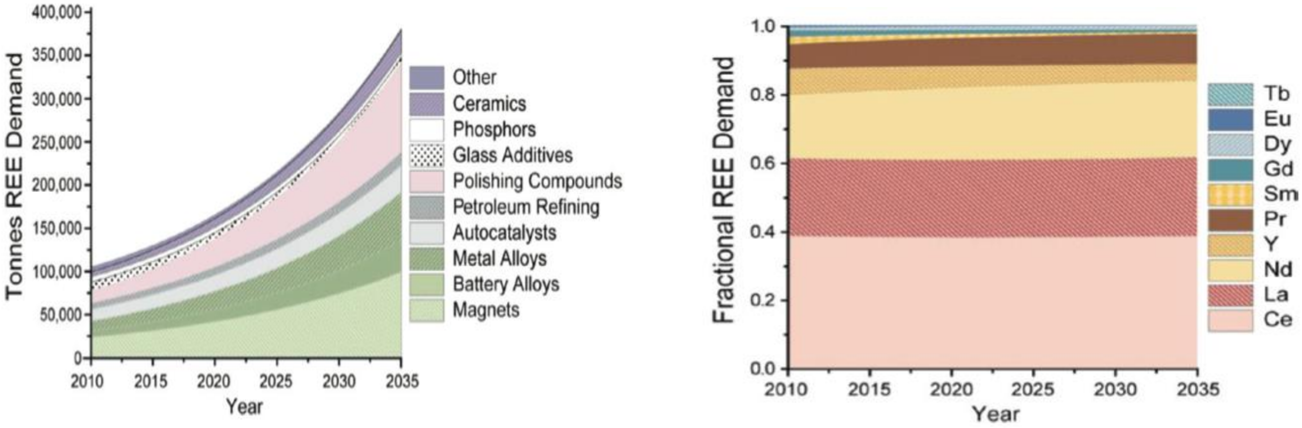


Figure 3. Projected total and fractional REE demand growth

Source: Alonso et al., 2012

There is an expectation of a significant increase in the usage of permanent magnets soon.

This is attributed to the global trend towards using environmentally friendly energy to decrease carbon emissions and promote sustainable growth. The areas that have the highest demand for rare earth elements (REEs) are permanent magnets, metal alloys, and catalysts. Neodymium (Nd)-based magnets are one of the most common permanent magnets and have a wide range of applications such as wind turbines, electric motors, hard disk drives, and magnetic resonance imaging (MRI) machines. Neodymium magnets are made from an alloy of neodymium, iron, and boron (NdFeB). Samarium (Sm) and Dysprosium (Dy) are also used in rare earth magnets. [3]

Various sectors of the economy experience varying rates of growth. Nevertheless, every sector relies on distinct rare earth elements (REEs). Consequently, the demand for a particular REE may become a significantly greater (or lesser) proportion of overall demand as time passes. To illustrate, by the year 2035, the demand for Neodymium (Nd) will constitute nearly 40% of the total demand for REEs, while it only accounted for 20% in the 2010s. [3]

1.1.2 Application of REEs

This section summarizes the key uses of rare earth elements, which have exceptional physical and chemical characteristics, making them valuable across multiple industries. These industries can be broadly classified into two categories: traditional and high-tech. The traditional industries, which include metallurgy, machinery, glass, ceramics, and the petroleum and chemical sectors, account for the bulk of the overall consumption of rare earth elements. REEs are typically used in mixed metals, alloys, oxides, and salts in these industries. On the other hand, high-tech industries such as phosphors, permanent magnets, batteries, the nuclear industry, and superconductive materials have emerged in recent years. [1, 2]

Permanent magnets

Rare earth permanent magnets, such as Sm-Co alloys and Nd-Fe-B alloys, have superior magnetic properties when compared to conventional magnets. These magnets are utilized in various applications, such as computer disk drives, speakers, magnetic resonance imaging (MRI), and wind turbines.

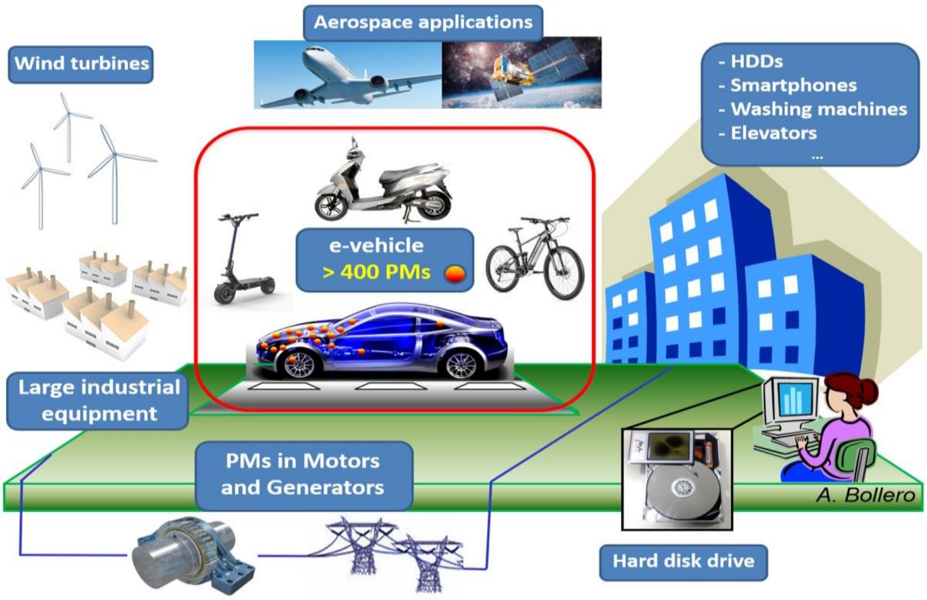


Figure 4. Applications of REEs

Catalyst

Lanthanum holds significant importance in fluid catalytic cracking, which is among the most crucial processes in the petrochemical sector. This process involves using a catalyst to transform heavy hydrocarbon fractions into lighter hydrocarbon compounds. Cerium (IV)-oxide, CeO_2, is, like La (III)-oxide, used in catalytic cracking of crude oil.

Figure 5. REE catalysts in petrochemical sector

Glass and Ceramics

This section explains how rare earth elements (REEs) are utilized in the glass and ceramics industries. REEs are used for various purposes like clarifying, coloring, polishing glass and creating pigments for ceramics. Cerium dioxide is specifically useful for clarifying and decolorizing glass, while other REEs can be used to give glass distinct colors. Lanthanum glass is ideal for making lenses due to its high refractive index. In ceramics, REEs are used to produce vibrant colors and to increase resistance to cracking. Yttrium oxide is added to zirconium oxide to make it suitable for use in high-performance ceramics.

Alloys

Rare earth elements (REEs) are also used in alloys, where they can improve the mechanical and physical properties of the materials. For example, adding tiny amounts of cerium to aluminum alloys can increase their resistance to corrosion and improve their high-temperature strength. Similarly, adding neodymium to iron-based alloys can improve their magnetic properties, making them ideal for use in motors and generators. REEs can also be used to produce high-performance permanent magnets, with samarium-cobalt magnets being a notable example. These magnets are highly resistant to demagnetization and can maintain their magnetic properties at elevated temperatures, making them useful for a variety of applications in the aerospace, automotive, and electronics industry. [2]

La	• Nickel metal hydride batteries (Prius, forklifts) • Hydrogen storage alloys $LaNi_3$ • Alloying agent • Sputtering targets • Optical lenses • Host for phosphors • Petroleum fluid catalytic cracking (FCC) • Cathode material in solid oxide fuel cell	Dy	• Additive to $Nd_2Fe_{14}B$ permanent magnets to improve high-temperature performance • Phosphors • Nuclear industry-radiation shielding

Ce	• Catalyst for automotive three-way-emission catalyst • Petroleum fluid catalytic cracking (FCC) • Glass additives • Decolorizer, opacifier • Ultraviolet light absorption • Polishing media for glass, lenses, semiconductors • Phospors	Ho	• Research • Metal halide lamps • YIG (yttrium-iron-garnet) lasers • YAG and YLF solid-slate lasers
Pr	• Additive to $Nd_2Fe_{14}B$ • Pr-stabilized ZrO_2 • Coloring agents • Telecommunication systems as dopant in fluoride fibers	Er	• Fiber optics-signal amplifiers • Lasers (mainly median/surgical and dental use) • Coloring agent
Nd	• $Nd_2Fe_{14}B$ permanent magnets • Alloying agent for Mg alloys • Lasers •	Tm	• X-ray intensifying screens • Metal halide lamps • Research
Sm	• SmCo permanent magnets • Coloring agent • Phosphors • Nuclear industry-radiation shielding	Yb	• Optical lenses • Pressure sensors (metal) • Research
Eu	• Phosphors (red) • Nuclear industry-radiation shielding	Lu	• Research • Host for scintillator detectors and X-ray phosphors
Gd	• Host for phosphors • Magnetic resonance imaging contrast agents • Nuclear fuel rod addition, safety • Laser YGG (yttrium-gadolinium-garnet)	Sc	• High-performance alloys • Lasers • Phosphors • Ceramics
Tb	• Phosphors (green) • X-ray intensifying screens • Magneto-restrictive alloy	Y	• Host for phosphors • YAG laser host material • Y-stabilized ZrO_2 • YBa_2CuO_2 high-temperature superconductor • Alloying agent

Figure 6. Overview of REEs applications

Source: Gupta and Krishnamurthy (2004).

1.2 Coal and coal ash

Coal is a naturally occurring combustible rock formed over millions of years from the decay of dead plants under pressure and heat. It consists of carbon, hydrogen, oxygen, nitrogen, sulfur, and other trace elements. Moreover, it is one of the most abundant and widely distributed energy resources in the world.

Coal is used in a wide range of applications such as electricity generation, heating, transportation fuel, chemicals, materials, and pharmaceuticals. Despite its various uses, coal is a non-renewable resource and its combustion releases greenhouse gases and pollutants that contribute to climate change and air pollution.

Coal ash is produced from the combustion of coal in coal-fired power plants. Coal combustion byproducts (CCBs) are residues generated during coal combustion for energy production. These residues include a range of materials such as fly ash, bottom ash, boiler slag, and flue gas desulfurization gypsum.

The fine particle ash that rises with the flue gas is called fly ash, while the heavier ash is the bottom ash. Fly ash is a heterogeneous mixture of amorphous and crystalline phases and is a Ferro aluminosilicate mineral with Al, Ca, Fe, K, Na, and Si as the predominant elements. [5]

Many studies have been published in recent years focusing on the recovery of rare earth elements (REEs) from coal-related materials, including coal, coal refuse, and coal combustion byproducts particularly fly ash.

Coal combustion byproducts (CCBs) are used in the construction industry. For example, fly ash and bottom ash can be used as replacements for cement in concrete production. Concrete pavements containing fly ash are exceptionally durable and cost effective. The largest use of CCP's (mostly fly ash) is in cement and concrete as shown in figure 7.

SI. No.	Mode of Utilization	China	India	European Union	United States
1	Cement	44	25.6	33.6	19
2	Mine filling	0	6.4	0	2.5
3	Bricks and tiles	28	9	0	
4	Reclamation of low-lying area	0	10.5	0	6.1
5	Ash dyke raising	0	6.9		
6	Roads and flyovers	5	3.4	16.4	2.8
7	Agriculture	3	0.3	0	0
8	Concrete	16	0.7	46.3	58.4
9	Hydro power sector	0	0.004	0	
10	Others	4	4.4	3.7	11.2
11	Unutilized fly ash	0	32.9	0	0
	Total	100	100	100	100
Estimated potential of REE (tons/annum)[a]		2,67,000	87,220	55,180	16,910

Figure 7. Utilization of Fly Ash During the Year 2017–2018

Source: Abhilash, Ata Akcil. Critical and Rare Earth Elements.

From 1950 to 1970, around 100 major dam construction projects used concrete with fly ash contents up to 50 percent. [7] As an example, the construction of Hungry Horse Dam in 1953 involved the use of 120,000 metric tons of fly ash shown in figure 8.

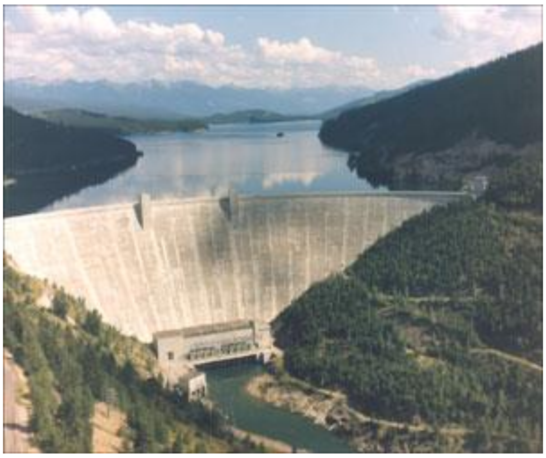


Figure 8. Hungry Horse Dam, Montana

1.2.1 Characteristics of fly ash

Physical Characteristics

Based on the type of coal combusted in thermal power plants, fly ash is classified into two types. Class F (low-lime/siliceous) fly ashes: It is produced from bituminous coal, which consists of spherical grains with a high content of glassy phase and contains low calcium and unburned carbon less than 5–10%. According to ASTM C618 classification, SiO_2+ Al_2O_3+ Fe_2O_3> 70% and as per the Canadian Standard Association (CSA), CaO < 18%. This fly ash has pozzolanic properties. On mixing with cementing agents like Portland cement or quicklime and water for reaction, it forms cementitious compounds

Class C (high lime/calcareous) fly ashes: It is produced from lignite of sub-bituminous coal, which contains higher calcium oxide and <2% unburned carbon. According to ASTM C618, SiO_2+ Al_2O_3 + Fe_2O_3> 50% and as per the CSA classification, reactive CaO> 18%. This fly ash has both pozzolanic and self-cementing properties. Hence, it hardens and becomes stronger over time in the presence of water. It is more commonly used for mixing in concrete/cement. [6]

Pozzolanic property: It refers to the ability of certain materials, such as fly ash, to react with calcium hydroxide in the presence of water to form cementitious compounds. This reaction can improve the strength and durability of concrete and reduce the amount of cement needed in the mixture. Materials with pozzolanic properties are commonly used as supplementary cementitious materials in concrete production.

Physical properties of typical coal fly ash

Property	Value
Density (g/cm^3)	2-2.8 (varies with Fe content and wt%.)
Bulk density (g/cm^3)	1.26 (affected by amounts of cenosphere and plerosphere in the fly ash)
Moisture content (%)	2
Particle shape	Mostly spherical (cenospheres and plerospheres). Minor unburned carbon particles irregularly shaped
Color	Dark Gray (F-class fly ash) Light Gray (C-class fly ash)
Porosity	45-55
Particle size (μm)	1-100
Specific surface area (cm^2/g)	1579-5550

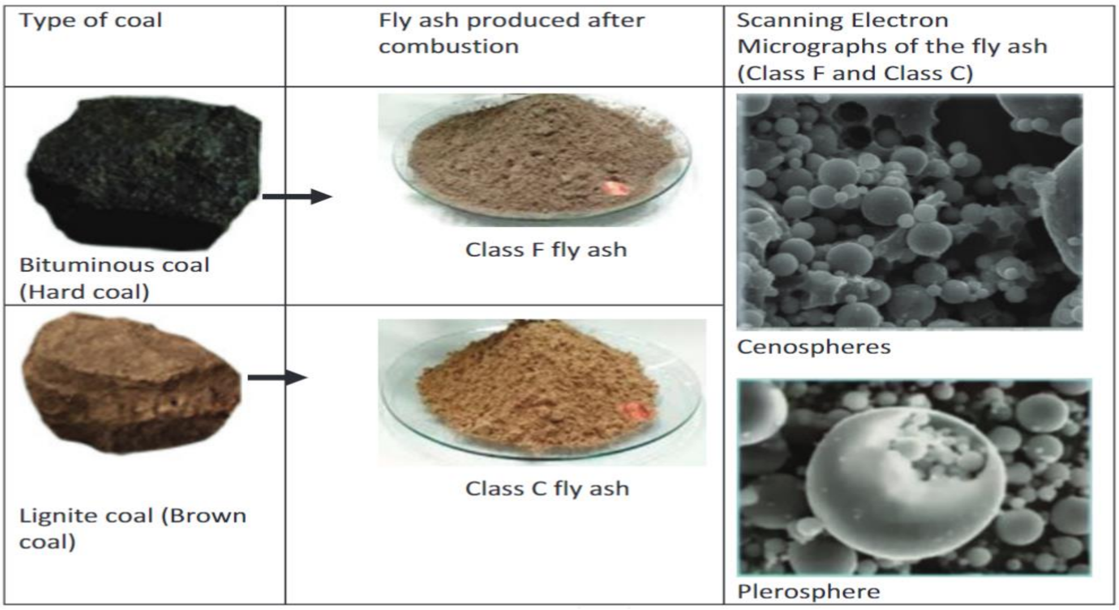


Figure 9. Physical property, color and morphology of the several types of coal and corresponding coal fly ashes, Type F and Type C.

Source: Adapted from Abhilash, Ata Akcil. Critical and Rare Earth Elements.

Chemical Characteristics

The chemical makeup of fly ash, which is affected by the type of coal used in the thermal power plant, is analyzed using X-ray fluorescence and spectrometry techniques. The primary elements found in CFA are SiO2, Al2O3, Fe2O3, and CaO, while other trace elements include MgO, Na2O, K2O, SO3, MnO, TiO2, and C.

Component	Class F	Class C
SiO_2	20-60	15-45
Al_2O_3	5-35	10-25
Fe_2O	10-40	4-15
CaO	1-12	15-40
MgO	0-5	3-10
SO_3	0-4	0-10
NaO	0-4	0-6
K_2O	0-3	0-4

Table 2 Normal Composition range of two types of CFA

Above the table is a typical composition of fly ash of bituminous coal. In this study, Class C light gray fly ash is used, and its major constituents are shown in table 2.

The characteristics of coal fly ash, such as its mineralogy, physical, and chemical properties, are influenced by the features and qualities of the original coal and the circumstances in which it was generated.

Sample	Element %										
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	MnO	SO_3
BN Coal	28.05	0.37	11.02	46.04	6.36	1.58	0.47	0.99	0.05	0.83	3.97
BAB	58.33	0.6	18.84	10.52	5.7	1.2	0.27	2.26	0.11	0.18	1.22
BAG	60.64	0.56	19.09	10.61	3.21	1.09	0.3	2.66	0.1	0.19	0.77
CFA	49.39	0.54	16.61	8.43	17.22	3.28	0.51	1.32	0.08	0.39	1.35

Table 3. Composition of Baganuur brown coal, IV thermal P.S fly ash and Baganuur bottom ashes

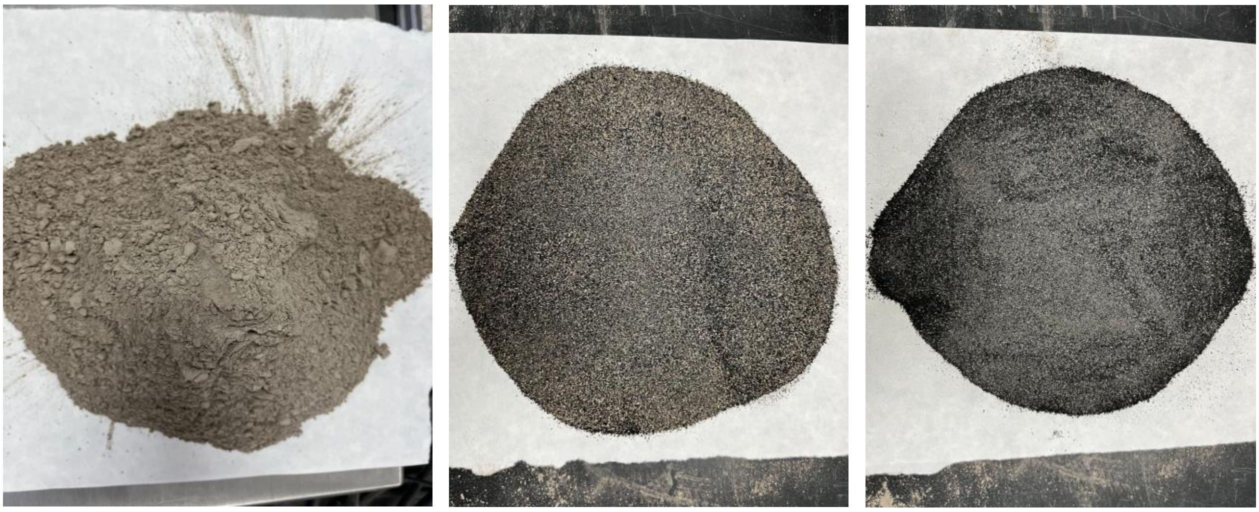


Figure 10. Coal Ashes: Fly ash,
Bottom Ash coarser (BAG) and Bottom Ash finer (BAB)

XRD and SEM analysis were conducted on coal, coal ash by Erdenet Mineral Research Institute.

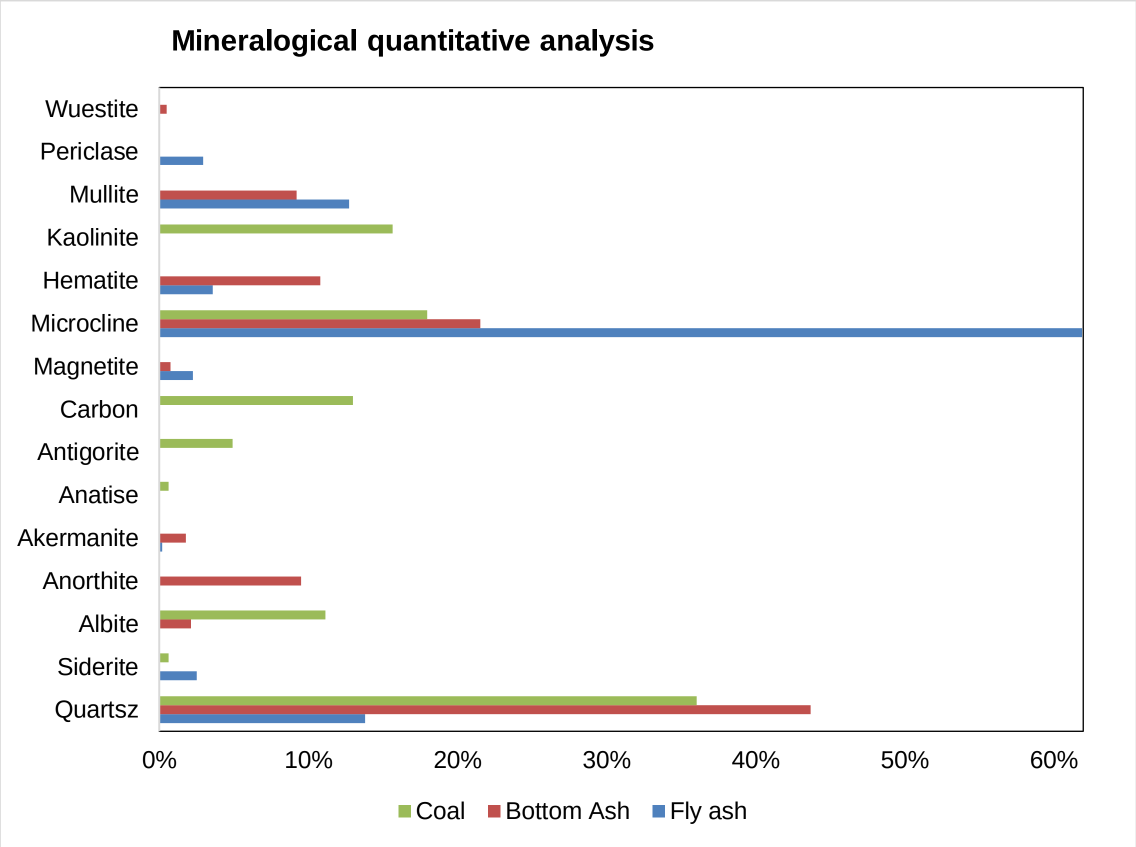
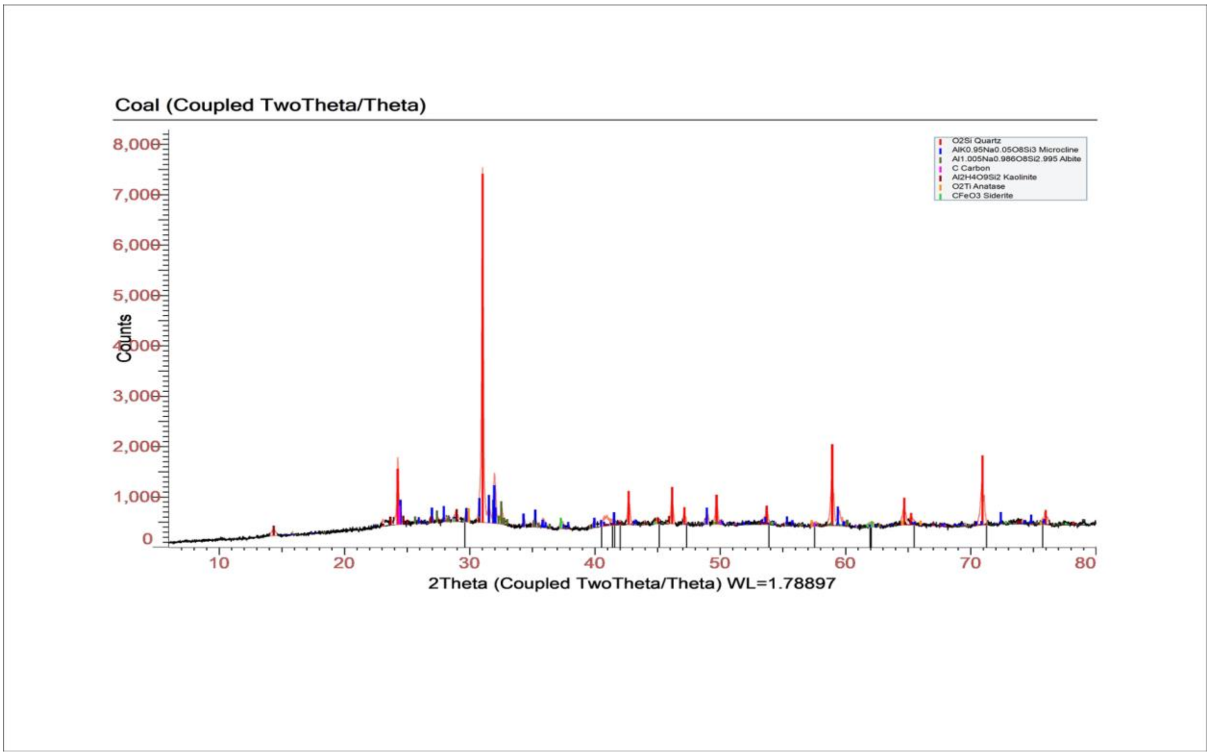


Figure 11. Mineralogical quantitative analysis

Microcline (61.92%), quartz (13.83%), and mullite (12.74%) and have been identified to be the three most common phases in the samples. These phases are mostly produced by the pyrolysis of clay minerals in coal (primarily kaolinite and illite) at high temperatures during the combustion process. Siderite, magnetite, hematite, and periclase also occurred in minor quantities (as listed in figure 11). These findings were supported by the results obtained from X-ray fluorescence (XRF) analysis. Highest peak intensity was observed at 31 degrees which corresponds to the presence of quartz mineral, indicating the existence of a noticeable glassy phase in the coal and CFA sample.



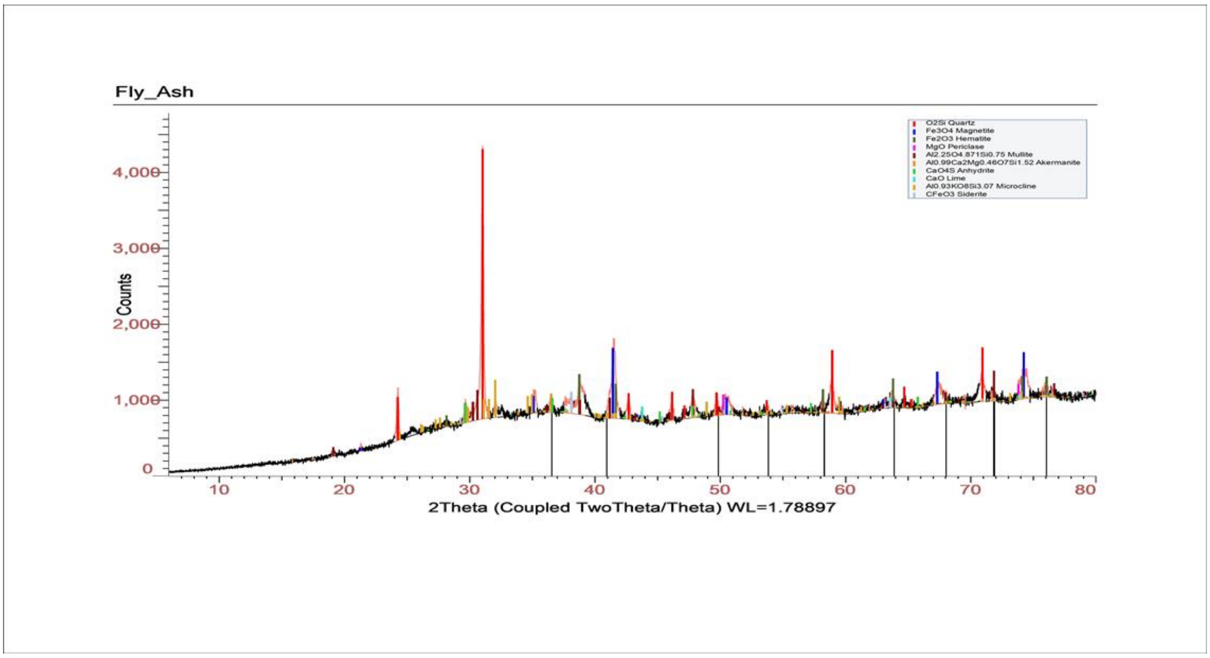
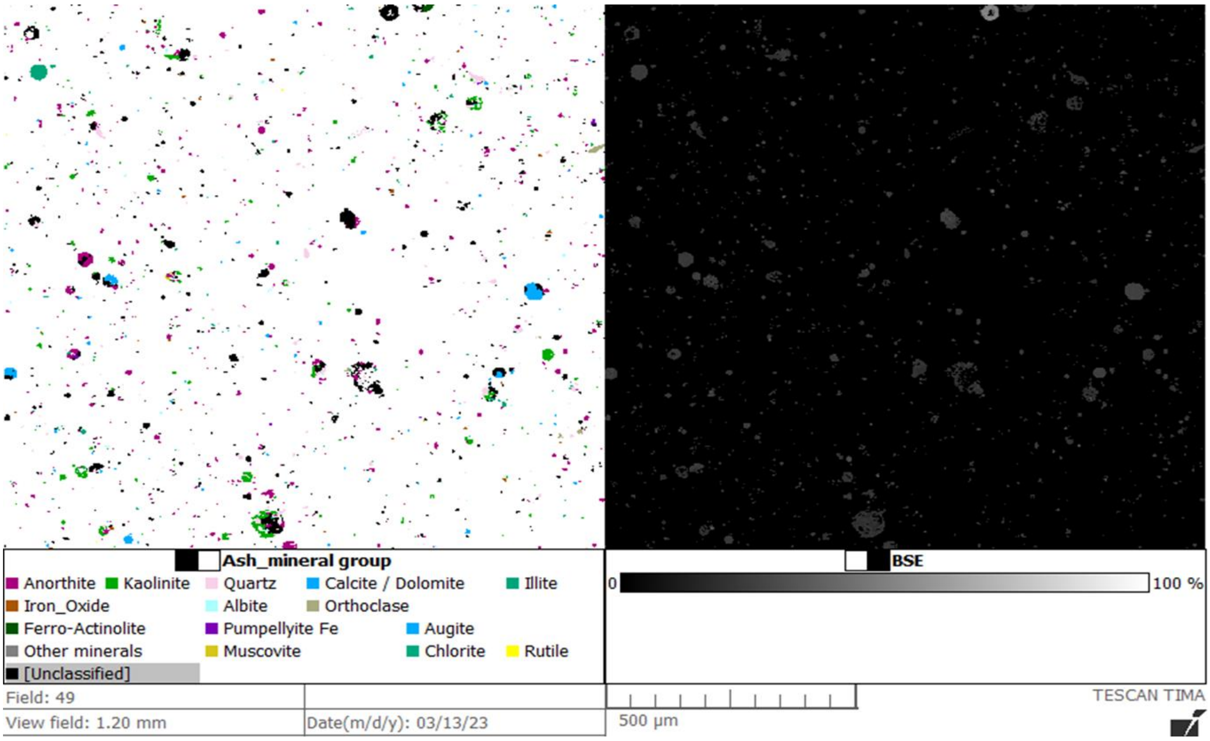


Figure 12. . XRD patterns of coal and CFA sample

SEM analysis is a versatile and powerful tool for material characterization. It can provide information about the surface morphology, elemental composition, and microstructure of a sample. The following figures indicate the SEM images of coal and CFA at different view fields and magnification.

Figure 13. SEM images of coal



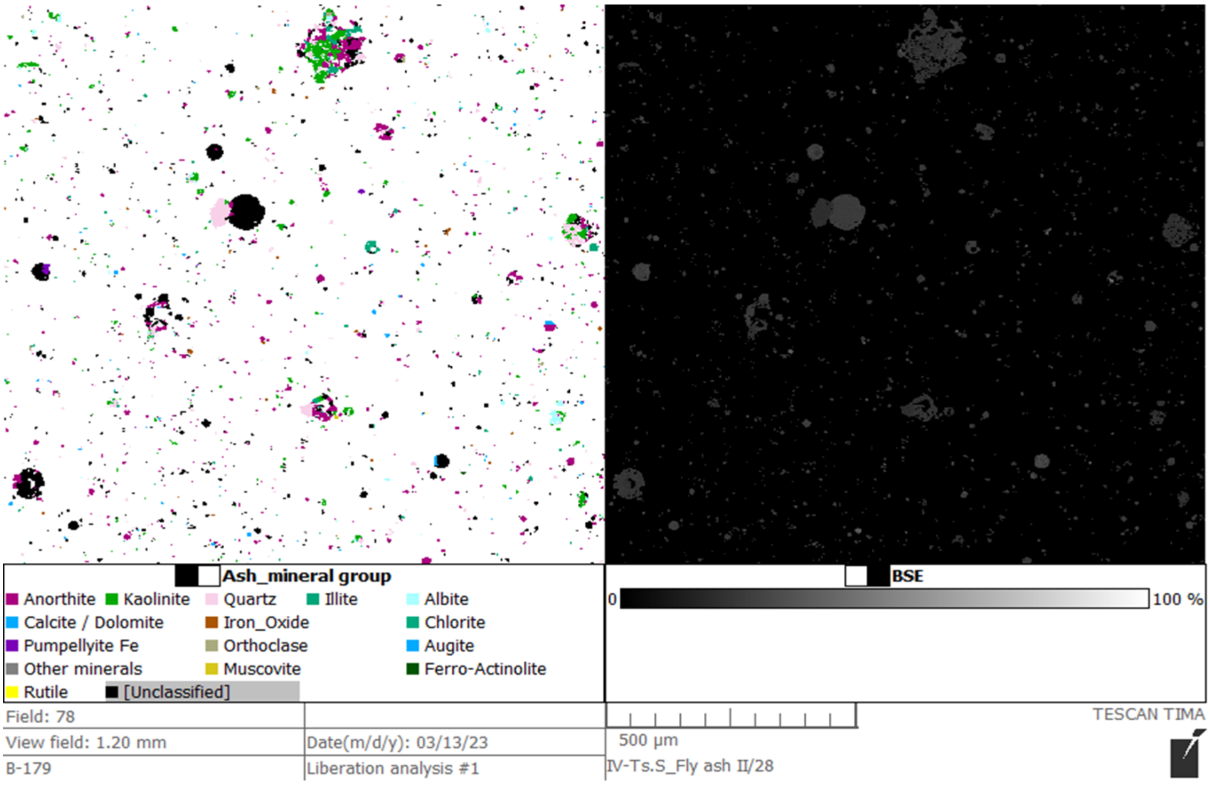
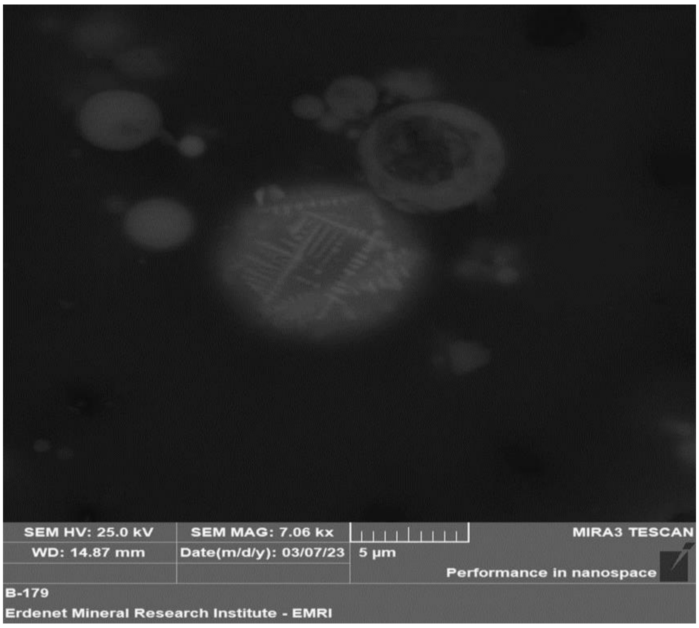
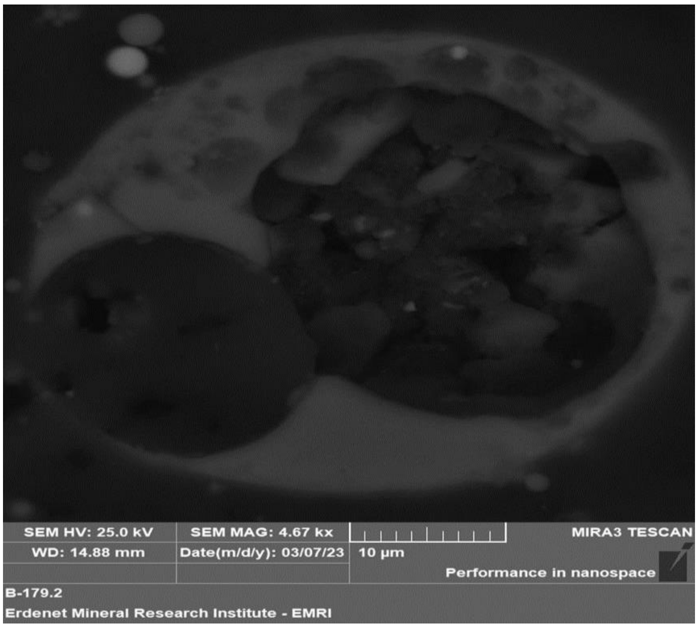


Figure 14. SEM images of coal fly ash

Here in this magnification, the CFA particles demonstrate spherical and porous morphology.





IV thermal power plant, Ulaanbaatar

The foundation of Thermal power plant No.4 was laid in 1979. The first unit was put into operation in 1983 and commissioned with a project capacity of 380 MW in 1987. As a result of expansion, the capacity was increased by 160 MW from 1988 to 1990, by 20 MW each in 2007 and 2009, by 120 MW from 2012 to 2014 and current operating capacity is 700 MW of electricity and 1373 GCal of heat generation in total.

The biggest power generation facility in the Mongolian energy sector is "Thermal power plant No.4" JSC. This plant produces more than 67.8 percent of the electricity for the central region and 60.3 percent of the heat required for consumption in Ulaanbaatar city.
Brown coal is the primary source of fuel that powers the “IV Thermal power plant”, resulting in the production of class C fly ash, which has a light gray color. This type of fly ash is utilized in this study. [15]

Figure 15. IV Thermal Power Plant, Ulaanbaatar

2. State of the art

In this section, the literature review of the physical beneficiation of REEs from coal ash based on the density, particle size, magnetism, gravity as well as surface hydrophobicity is described. To investigate, the REEs in fly ash are more concentrated in the finer fractions relative to the entire bulk material. The finer fractions in fly ash usually contain more glass phases relative to the coarser fractions, while REEs are preferentially associated with the glass phase in fly ash. In dense medium separation, sink particles contain more REEs while float particles contain less. In magnetic separation, the magnetic fraction contains fewer REEs relative to the bulk fly ash while REEs are more enriched in the weak and non-magnetic fractions. Flotation tests using different collectors with different conditions also produced a series of products with different REE contents. With these results, physical separation methods can be used to pre-concentrate REEs from coal combustion ash, in that way providing a higher-grade feed material to further extraction processes such as leaching. Despite the physical beneficiation, chemical extraction methods also give better results, for example leaching by acid combined with alkali pretreatment rather than direct leaching of the ash to recover REE. [9, 10, 11]

2.1 Mineral processing

Mineral processing is the process of separating valuable minerals from their ores. Ores are naturally occurring rocks or minerals from which metal or other substances can be extracted. Mineral processing involves several stages, including crushing and grinding the ore to a fine size, separating the valuable minerals from the gangue or waste materials, concentrating the valuable minerals into a product of higher value, and finally, refining the concentrate to produce a pure metal or other product. Each rare earth deposit is unique and is always composed of a variety of minerals. To make rare earth production economically feasible, a series of ore beneficiation techniques are always required to concentrate the rare earth minerals. The commonly used ore beneficiation technologies include gravity separation, flotation, and magnetic separation. Chemical extraction methods are used to extract REEs from the separated minerals. The most common extraction method is acid leaching, where the minerals are treated with acid to dissolve the REEs. Moreover, solvent extraction (SX) or liquid–liquid extraction is a practical and effective technology for massive REE separation. SX is the dominating process in the current industry practice. The purity of the REE products is up to 5 N but in limited quantities due to its low capacity and low efficiency. [1] (2N indicates a purity of 99%, 2N5=99.5%, 5N8=99.9998%, 5N=99.999%).

2.2 Recovery of REE from coal fly ash

A substantial portion of the world's electricity is generated by coal-fired power stations, which also generated approximately 1 billion tons of fly ash in 2017. [6] The total annual electricity generation, percent contribution by coal combustion, and the consequent fly ash generation across major countries in the world are presented in table 4.

	China	India	European Union	United States	World
Annual electricity production (TWh/annum)	6,529	1,541	3,886	8,182	25,551
% contribution of electricity by coal combustion	66.5	76	20.6	26	27
Coal fly ash generation (Million tons/annum)	600	196	124	38	958

Table 4. Annual Electricity Production, % Contribution of Electricity by Coal Combustion, and Coal Fly Ash Generation in Major Coal Combustion Countries During the Year 2017

In 2011, just under half of the coal fly ash (CFA) generated was used in construction projects such as cement and road building, with the rest stored in ash ponds, which poses environmental risks. The typical concentration of rare earth elements (REEs) found in CFA around the world is 400 parts per million (ppm). [6]

There is a growing interest in recent research studies to develop processes for recovering rare earth elements (REE) from secondary sources such as recycled REE magnets, fluorescent lamps, batteries, alloys, catalysts, and phosphorus-based products. Coal fly ash (CFA) is one such secondary source generated in large quantities at thermal power plants worldwide. Extracting REE from CFA has several advantages over conventional extraction methods from primary deposits. Firstly, REE present in CFA can pose an environmental threat. Secondly, CFA contains the full range of REE, while conventional minerals like bastnaesite, monazite, and xenotime contain only selected REE. Additionally, the percentage of critical elements in CFA samples is higher (34%-38%) compared to conventional REE deposits globally (<15%). Finally, as CFA is available in powder form, it presents fewer environmental challenges than those associated with traditional mining and processing of primary REE deposits. [6] As a result, extracting REE from CFA is an environmentally friendly and cost-effective alternative to conventional extraction methods.

The extraction of REE from CFA is still in its research stage and not yet commercialized. Researchers have suggested several processing routes including hydrometallurgical methods to recover REE from this secondary source of rare earths.

Elevated temperature and pressure roasting/leaching are required to split up the glassy alumino-silicate lattice structure in which the REEs are embedded. Followed by hydrometallurgical methods using three different commercial acids (H_2SO_4, HCl, and HNO_3).

After leaching, the solution is purified to remove impurities and other unwanted elements. Several techniques such as solvent extraction, ion exchange, and precipitation can be used for purification. Finally, the purified REEs are recovered by precipitation or other methods.

Recovery of REEs from CFA is an environmentally friendly and cost-effective alternative to conventional extraction methods from primary deposits. [6] This method also has the added advantage of reducing the environmental impact of CFA, which is often disposed of in landfills, creating potential hazards to the environment. Figure 16 below shows an example recovery of REEs from CFA.

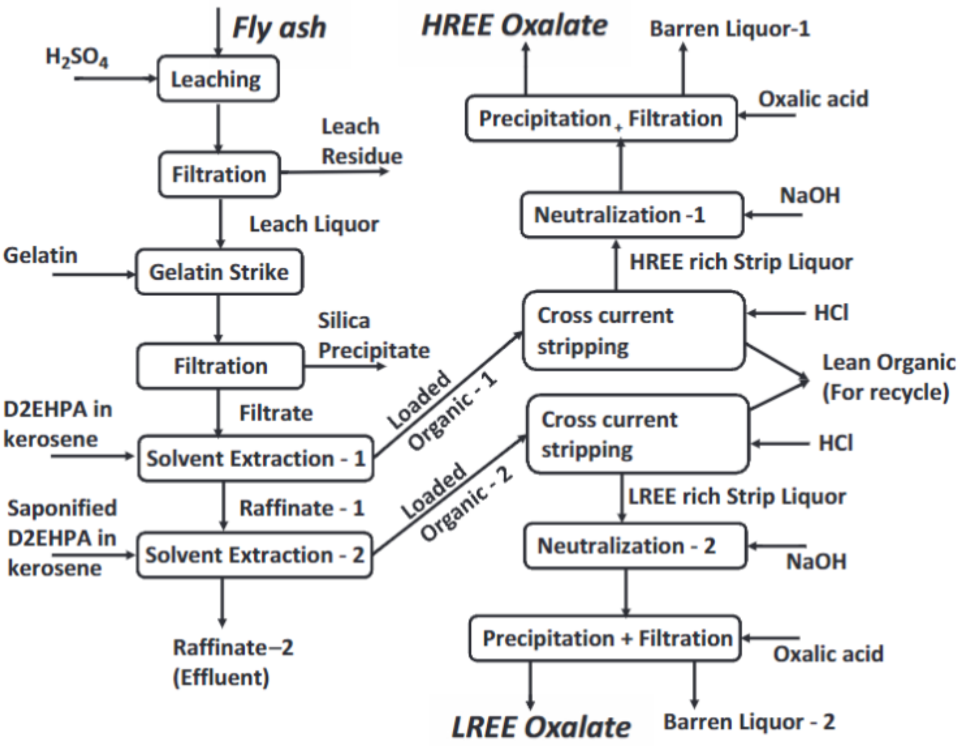


Figure 16. Process flowsheet for recovery of REEs from an Indian CFA

Source: Adapted from Abhilash, Ata Akcil. Critical and Rare Earth Elements

CFA after leaching by sulfuric acid. The formation of a gel was prevented during the purification process of rare earth elements (REEs) by using gelatin to sequester the dissolved silica. The purification process involved solvent extraction using DEHPA and kerosene as a diluent. Partial saponification of DEHPA was necessary for complete loading of LREE, while HREE could be loaded directly. The extraction sequence resulted in 90% total REE extraction. Stripping of the loaded REEs was carried out using a 6 *M* HCl solution, resulting in near-complete recovery of REEs in corresponding aqueous phases. The purified aqueous phases were neutralized with NaOH and subjected to precipitation of REEs using oxalic acid solutions. This process produced an LREE oxalate analyzing 17.5% LREE and an HREE concentrate assaying 13%.

2.3 Fly Ash Beneficiation for REE Recovery

2.3.1 Physical separation method

Several studies have been performed to concentrate Rare Earth Elements-bearing mineral particles from coal and coal combustion byproducts using physical beneficiation techniques such as sieving, magnetic separation, gravity separation and flotation. Sieving involves the separation of distinct size fractions of the fly ash particles, which can aid in subsequent separation processes. To investigate, the REEs in fly ash are more concentrated in the finer fractions. Magnetic separation uses magnetic properties to separate the magnetic components of the fly ash from the non-magnetic components. REEs are more concentrated in non- magnetic fractions. [9, 12] Gravity separation takes advantage of the differences in density between the various components in the fly ash to separate them. In the process of CFA beneficiation by gravity concentrators such as shaking table, Knelson concentrator, the REEs are more concentrated in the heavy fraction. Froth flotation is normally utilized to treat fine particles based on their varying degrees of surface hydrophobicity. In the froth flotation process, the concentration and recovery of REEs in fly ash differs by changing the pulp pH, reagents, and its dosage. These methods can be combined to achieve better results for further extraction of REEs from CFA.

2.3.2 Chemical separation method

Chemical processes include leaching, precipitation, and solvent extraction. Acid leaching involves strong acids to dissolve the REEs and other valuable metals in the fly ash. The resulting leachate can then be subjected to precipitation, where specific metals or impurities can be selectively removed by adding a suitable reagent. Solvent extraction uses an organic solvent to selectively extract the REEs from the leachate, which can then be further processed to obtain pure REE compounds.

Several studies have reported that REE recovery from fly ash was improved by alkali roasting treatment prior to acid leaching. Roasting breaks down the glassy structure of fly ash and liberates the REE-bearing particles. [10, 11] Alkali leaching is a process used to extract metals, including rare earth elements (REEs), from ores or secondary sources using a basic solution such as sodium hydroxide. The process involves the breakdown of the ore or mineral through chemical reactions in the basic solution. The leaching process makes the REEs soluble in the basic solution, which can then be separated by further processes such as solvent extraction.

Solvent extraction is a technique used for the separation and concentration of specific rare earth elements from others by taking advantage of the partition of the elements between two immiscible phases. Typically, the feed consists of an aqueous solution containing valuable metals, free acid, and impurities dissolved in water. Meanwhile, the organic solution consists of an extractant, and a modifier dissolved in a diluent or carrier. The diluent or carrier is a liquid or homogeneous mixture of liquids that forms the primary component of the organic phase. [1]

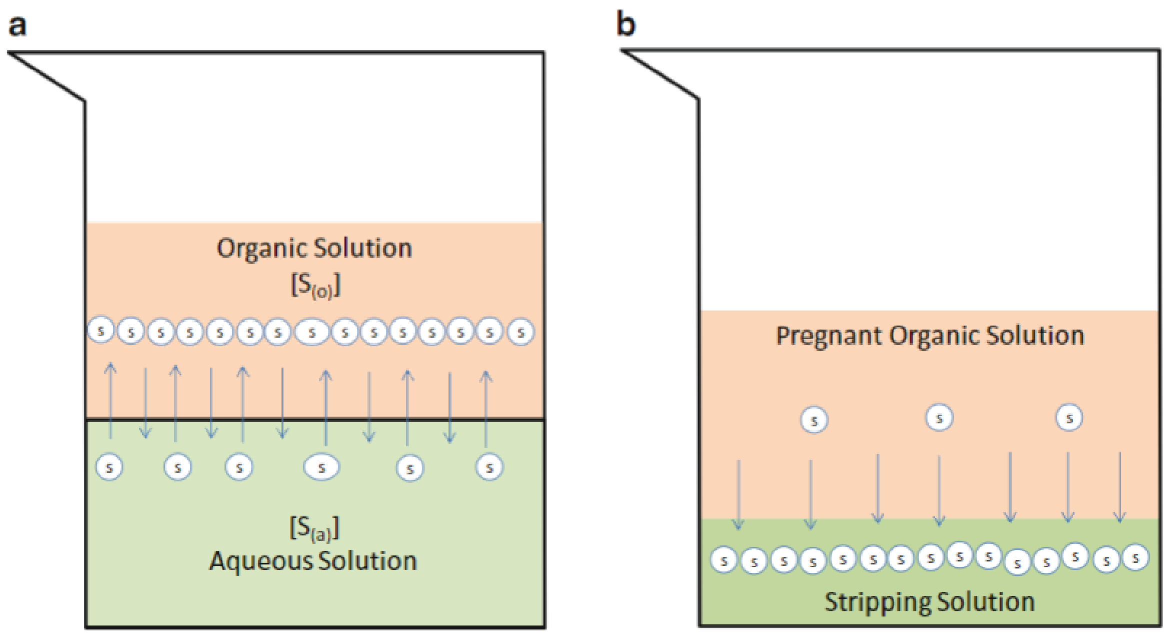


Figure 17. Schematic representation of solvent extraction principle

Source: Adapted from Zhang J, Zhao B, Schreiner B. Separation hydrometallurgy of REEs

The primary components of diluents utilized in solvent extraction are crude oil fractions comprising a blend of aliphatic, naphthenic, and aromatic constituents. The active element in the process is known as the extractant and is responsible for transferring metals from the aqueous solution to the organic phase. Common extractants such as LIX 63, DEPHA, HTTA, A336. [13]

The solvent extraction process typically involves several stages, including leaching, extraction, scrubbing, and stripping. Here is a brief overview of each stage:

- **Leaching**: In this stage, the ore is treated with an acid or alkaline solution to dissolve the REEs and other metals. The resulting solution, known as the leachate, contains the dissolved REEs.

- **Extraction**: The leachate is then mixed with an organic solvent that selectively extracts the REEs from the solution. The most common solvent for REE extraction is a phosphoric acid-based extractant.
- **Scrubbing**: The extracted REEs are then scrubbed with a secondary solvent to remove any remaining impurities.
- **Stripping**: The purified REEs are then stripped from the organic solvent using an acid solution. The resulting solution contains the REEs in their purified form.

The solvent extraction process can be used to extract a wide range of REEs, including neodymium, praseodymium, dysprosium, and terbium, among others. The process is highly efficient and can produce high-purity REEs suitable for use in a variety of applications, including magnets, catalysts, and electronics. Solvent extraction or liquid-liquid extraction is the most common technology for extracting REEs in industries.

3. Methodology

The purpose of this thesis is to investigate the rare earth elements from coal and coal combustion byproducts from the Baganuur coal mine and Baganuur thermal power station and IV thermal power station, UB. In addition, this study aims for the physical beneficiation of fly ash due to its high REE content and effectiveness for further processes rather than bottom ash. Moreover, flotation tests are the main study of this work. Overall, the experiments include sample preparation using a riffle splitter, particle size analysis, froth flotation, magnetic separation, and gravity concentration all of which are covered in this chapter of the thesis. This section describes the materials, equipment, and experimental procedure used in the study.

The following methodology was used in reviewing the test results:

- Comparison of TREE content from different fractions of particle
- Relationship between REEs recovery and different conditions of flotation tests
- Relationship between REEs grade and different conditions of flotation tests.
- Comparison of determined TREE and results of physical separation methods

The recovery of the results calculated from the following equation:

$$Average\ grade = \frac{C * c + T * t}{F}$$

$$Recovery = \frac{C * c}{F * Average\ grade} * 100$$

Where, C=Concentrate (g), c=grade of concentrate

T=Tailing (g), t=grade of tailing

F=Feed (g)

3.1 Sample preparation

The sample preparation was completed at the mineral processing laboratory of German-Mongolian Institute for Resources and Technology. There are several methods of sampling such as grab sampling, cone and quarter, riffle splitting, and rotary riffle. To make a homogenized, representative sample for further processes we chose cone and quartering with a riffle splitter in this study. The technique involves shaping the sample into a conical form and then pressing it to form a cake. The Riffle splitter comprises a rectangular chute with a series of V-shaped dividers evenly spaced. The sample is poured at the top of the chute, and as it passes through the dividers, it is divided into smaller portions.

Firstly, we mixed the bulk sample, and it became conical shaped then we flattened and divided it into smaller fractions like the shape of the cake. After that, we took 10kg of the sample and divided it into smaller fractions through the riffle splitter. So, we repeated this action several times and, in the end, we also got several 1kg of representative samples. Then we dried each sample in the dryer at 105℃ to remove some moisture content.

Finally, we used these methods to get 1kg of fly ash sample and on that sample, sieve analysis was performed to determine the P80 which was below 75 microns which is the desired size for our further processes.

3.2 Sieve analysis

Sieve analysis is a technique used for determining the particle size distribution of a material. It involves the use of a set of sieves with different-sized openings arranged in a stack, with the largest sieve on top and the smallest on the bottom. The material to be analyzed is placed on the top sieve and then shaken for a set amount of time. The material that passes through each sieve is collected and weighed, and the weight percentage of material that passes through each sieve is determined.

There are two main types of sieve analysis:

Wet Sieving: In this method, the material to be analyzed is suspended in a liquid and poured onto the top sieve. The liquid helps to break down any agglomerates of particles, allowing for a more accurate analysis of the particle size distribution.

Dry Sieving: In this method, the material to be analyzed is simply poured onto the top sieve and shaken for a set amount of time. Dry sieving is more commonly used than wet sieving, as it is faster and easier to perform.

In this study, we used dry and wet sieving methods combined for better results. Sieves with opening sizes of 150μm, 106μm, 78μm, 38μm, and 20μm are used in this experiment and water is used as a working liquid because it is the most used liquid in wet sieving.
In dry sieving, we used a sieve shaker from Retsch for 1 hour and at an amplitude of 80. After the dry sieving test is finished, we continue with a wet sieving method starting from the finest to coarsest size sieves by washing the material with water so that any remaining particles with coarser size will be removed through the sieve which allows more accurate results.

Finally, the particles retained on each sieve were collected in different vessels with water after the wet sieve had finished. Then each of them is filtered and dried at 105℃ for 9 hours. After that, we weighed each sample on KERN FKB balance and performed particle size analysis.

3.3 Magnetic separation and Gravity concentration

Magnetic separation and gravity concentration experiments were conducted at "Central Geological Laboratory". The samples were prepared and sent to the laboratory for these methods. Gravity separation was accomplished using a shaking table and a Knelson concentrator, while magnetic separation was performed at varying magnetic field intensities of 0.5T and 0.16T. The results obtained from the magnetic separation experiment have been included in this study.

3.4 Flotation

In flotation, a mixture of ore or mineral particles and water is added to a vessel containing a flotation reagent, which is a chemical substance that enhances the hydrophobicity of the mineral particles. Air is then introduced to the vessel to generate bubbles, which selectively adhere to the hydrophobic mineral particles and float to the surface of the liquid, forming a mineral-rich froth. The froth is then collected and further processed to separate the valuable mineral from the unwanted material.

In this study, single stage flotation tests on fly ash were conducted using a D12 flotation machine by METSO and a flotation tank with a volume of 1.8L. The tests were carried out at various pulp pH levels ranging from 12 to 8. The impeller rate was set between 659 and 800 (rpm), and the air flow rate varied from 0.1m^3/h to 0.3m^3/h. Collector reagent, such as Sodium Oleate ($C_{18}H_{33}NaO_2$) was used with a dosage of 1000 g/t, Sodium silicate with a dosage of 500g/t as depressant, MIBC 50g/t was utilized as a frother and Hydrochloric acid (HCl) was added to adjust the pH. Moreover, all experiments were carried out using a liquid-solid ratio of 7:3, and the reagents were added with a 5-minute interval. The froth was collected for 10-15 minutes. Concentrate and tailings were separately filtered and dried at 105℃. After that, each sample is weighed and bagged for further chemical analysis. Process flow sheet of flotation test shown below in figure 18.

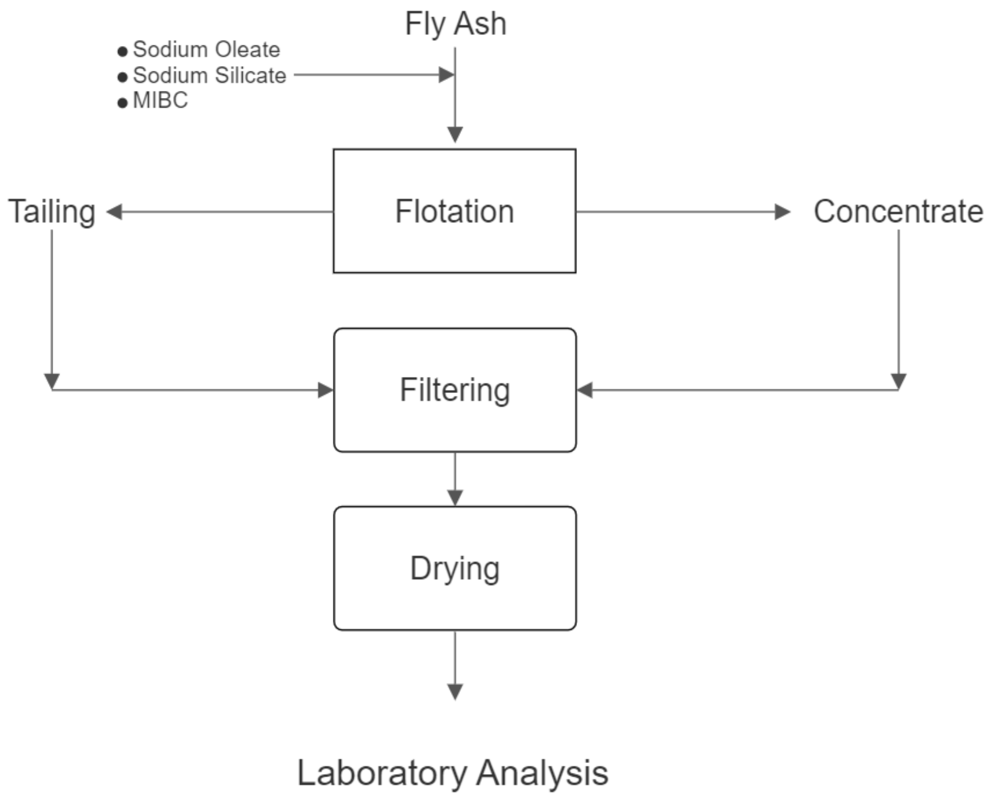


Figure 18. The process flow sheet of flotation test

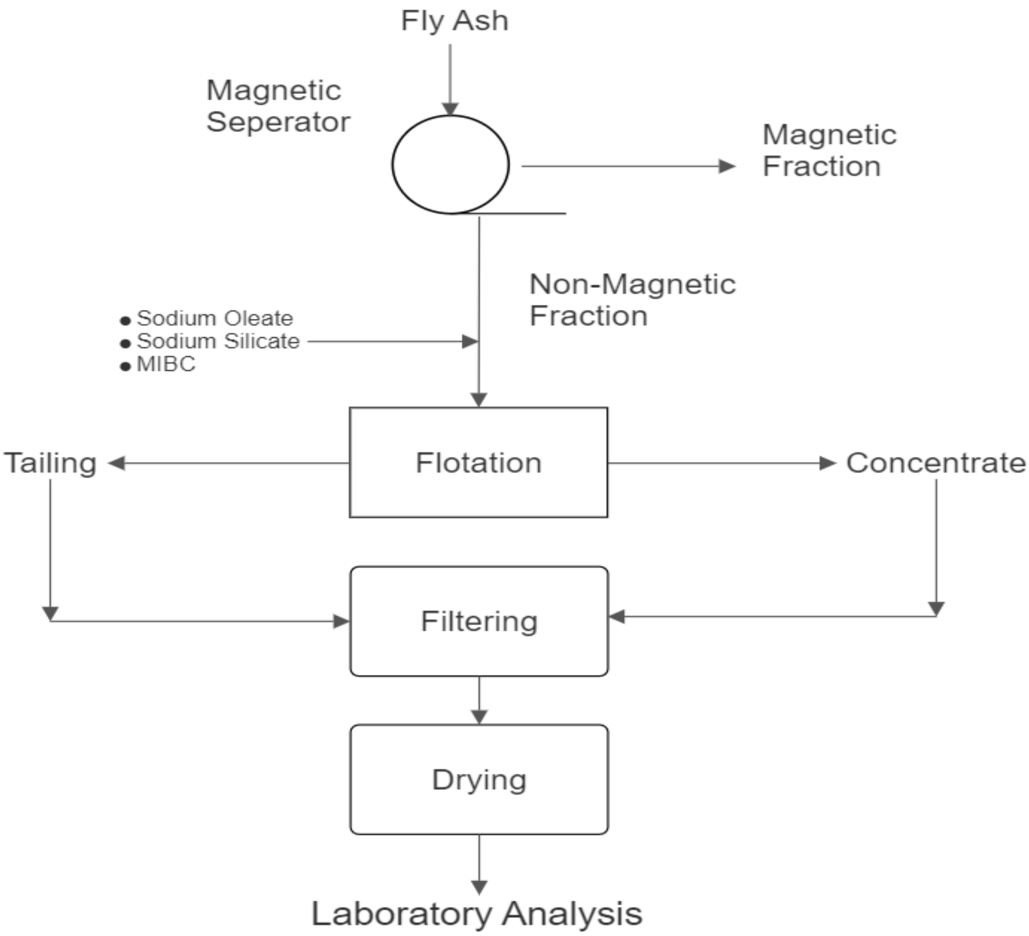


Figure 19. The process flowsheet of flotation test combined with magnetic separation

The following specifications apply to flotation tests:

- Feed mass: 540g
- Feed size: -75µm
- Percent solid: 30%
- pH: 8 to 12
- Collector: Sodium Oleate
- Frother: MIBC (Methyl isobutyl carbinol)
- Conditioning time: 5 min
- Agitation: 659 to 800 rpm
- Froth collecting time: 10 to 15 min

Fixed parameters		
Reagent	Dosage (g/t)	Conditioning time (min)
Collector, Na Oleate	1000	5
Depressant, Na Silicate	500	
Frother, MIBC	50	

When considering the reagent scheme for the flotation test conditions, collector, depressant and frother doses are fixed parameters in this test work.

Flotation Test №	pH	Modifier (ml)	Conc	Tailing
2	12	1M HCl, 40	80.2	443.3
3	12	~	346.3	185.1
10	12	~	364.2	169.1
7	11	1M HCl, 70	143.5	387.1
9	10	1:1HCl, 16	76.7	434.8
4	10	1:1HCl, 16	88.8	438.7
8	9	1:1 HCl, 34	63.5	454.6
6	8	1:1 HCl, 45.4	53.5	451.8

Table 5. Flotation test conditions

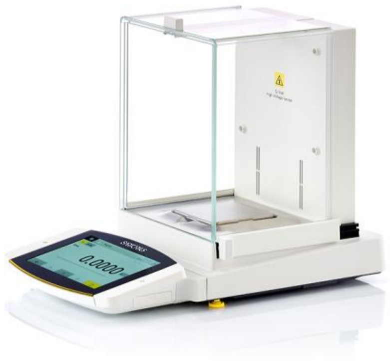
The table presented above provides information on various flotation tests. Tests 2, 3, and 10 were carried out at a pulp pH of 12. During test 2, 40 ml of 1M HCl was added to the pulp, which did not affect the pulp pH, but resulted in a lower concentrate. Test 10 involved using CFA particles smaller than 38μm without a pulp pH modifier, and to reduce the pulp pH, a more concentrated HCl was used. Test 9, however, involved non-magnetic CFA particles and was conducted at pH 10. The outcomes of these tests are detailed in the following section.

Figure 20. Flotation test progress

Equipment and Reagents

Metso® D12 Laboratory Flotation Machine

SARTORIUS- PB-10 pH meter



SARTORIUS analytical balance

Lichen technology electric blast drying oven

A Sieve shaker from Retsch

KERN FKB balance

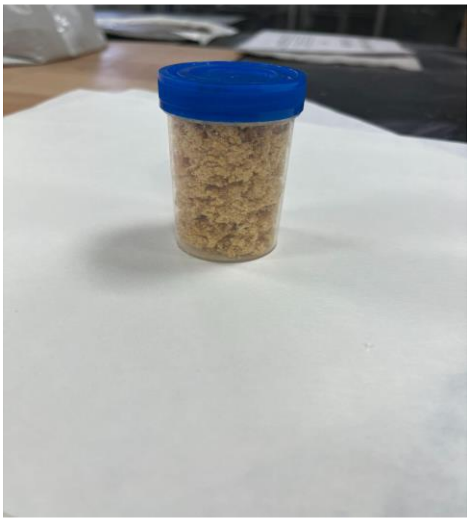
Figure 21. Equipments

Collector: Sodium Oleate ($C_{18}H_{33}NaO_2$)

Sodium oleate ($C_{18}H_{33}NaO_2$) is a common collector used in froth flotation to selectively recover rare earth elements (REEs) from their ores or industrial byproducts. It is a sodium salt of oleic acid, a fatty acid commonly found in animal and vegetable fats and oils.

In REE flotation, sodium oleate selectively adsorbs onto the surface of the REE-bearing minerals, forming a hydrophobic layer that attaches to air bubbles introduced into the flotation cell. As the air bubbles rise to the surface, they carry the hydrophobic particles with them, forming a froth layer that can be collected and further processed to separate the REEs from other minerals and impurities.

The dosage of sodium oleate used in REE flotation can vary depending on the specific ore or feedstock being processed, but typical dosages range from 100 g/t to 2000 g/t. Other factors, such as the pH of the pulp and the presence of other reagents, can also affect the effectiveness of sodium oleate as a collector in REE flotation. Sodium oleate was mixed with 50 ml of water and added to the flotation tank.



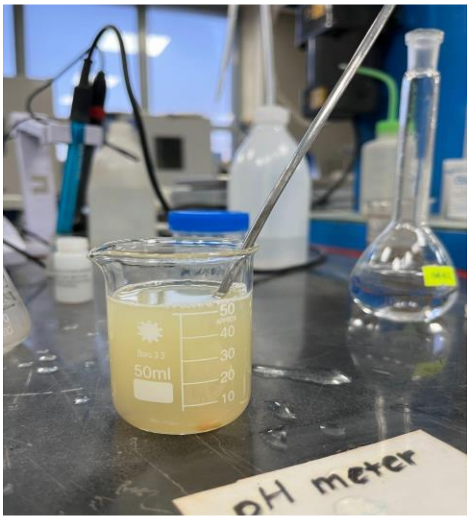


Figure 22. Sodium oleate

Frother: MIBC

Methyl isobutyl carbinol (MIBC) is a frother commonly used in mineral flotation processes. It is a clear, colorless liquid with a mild odor and is miscible with many organic solvents. MIBC is added to the flotation cell to stabilize the froth and enhance the kinetics of the flotation process by increasing the persistence of the air bubbles, which carry the hydrophobic particles to the surface

Depressant: Sodium silicate

Sodium silicate, also known as water glass, is a compound composed of sodium oxide and silica. It is a colorless, odorless, and viscous liquid that has a variety of uses. In the context of mineral processing and froth flotation, sodium silicate is often used as a depressant to inhibit the flotation of certain minerals, such as silica, so that other minerals can be selectively floated. Sodium silicate works by forming a thin film of silica on the mineral surface, which makes it less hydrophobic and thus less likely to attach to air bubbles during the flotation process.

3.5 Laboratory element analysis

Laboratory elemental analysis determines the sample's elemental composition by various analytical techniques. This involves the determination of the presence and quantity of individual elements in a sample, usually using instrumentation such as atomic absorption spectrophotometers, inductively coupled plasma (ICP) spectrometers, X-ray fluorescence (XRF) analyzers, and other specialized laboratory instruments.
Materials produced from each test were analyzed by ICP-OES in the Khanlab LLC.

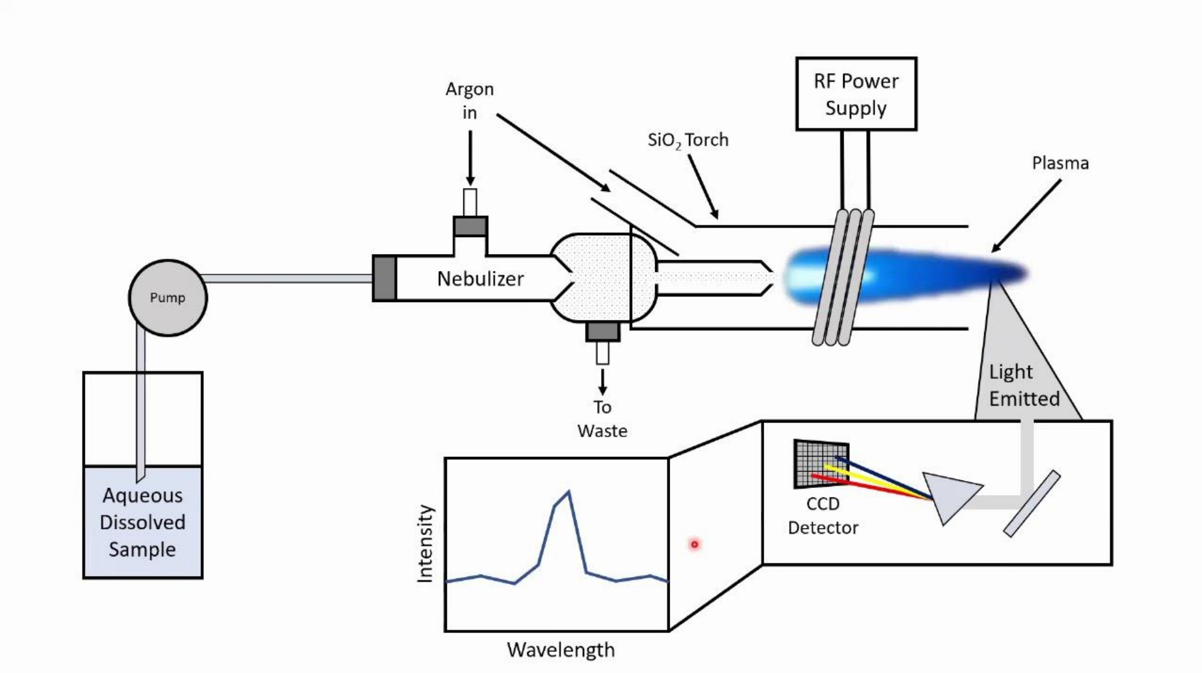
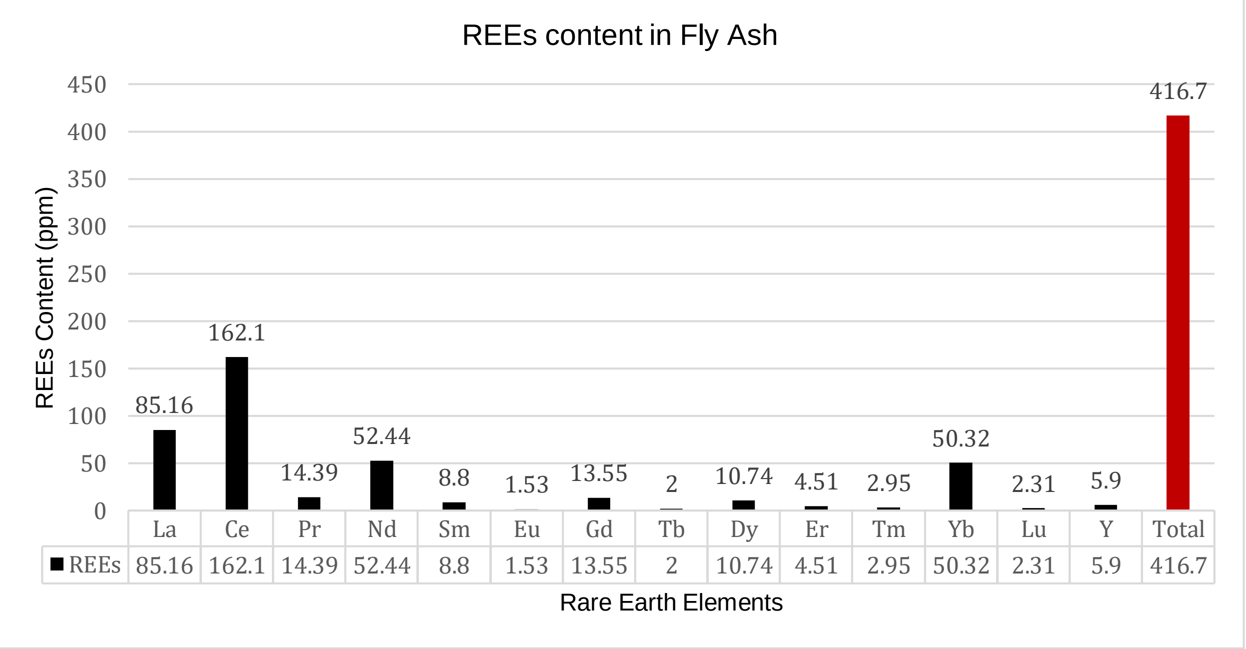


Figure 23. Working principle of ICP-OES

ICP-OES stands for Inductively Coupled Plasma Optical Emission Spectroscopy. It is a type of analytical technique used to determine the elemental composition of a sample. In ICP-OES, a sample is first dissolved in a liquid and then introduced into a plasma source where it is atomized and excited by high-temperature plasma. The excited atoms emit characteristic light at specific wavelengths, which can be detected and measured by a spectrometer. The resulting emission spectrum provides information about the elemental composition of the sample. [14]

4. Experimental Results and Discussion

According to figure 23, most rare earth elements (REEs) found in the coal fly ash (CFA) sample are Ce (162.1 ppm), La (85.16 ppm), Nd (52.44 ppm), and Yb (50.32 ppm). These four elements represent the highest concentrations of REEs in the sample and make up a sizable portion of the total REE content. The sample taken from the entire bulk fly ash results 416.7(ppm) of total REEs.



	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Er	Tm	Yb	Lu	Y	Total
REEs	85.16	162.1	14.39	52.44	8.8	1.53	13.55	2	10.74	4.51	2.95	50.32	2.31	5.9	416.7

Figure 24. REEs composition of CFA sample, REEs

4.1 Particle size analysis

The sieve size ranges of 150μm, 106μm, 75μm, 38μm and 20μm are used in the test.

The weight of material in each size range, for example, 14.2 g of material passed through the 106 μm sieve but was retained on the 75μm sieve, indicating that the material is in the size range - 106μm to 75μm. The results of a sieving test are plotted graphically to assess their full significance. The particle size distribution curve is plotted cumulative undersize versus particle size.

Sieve size (μm)	Sieve fractions		Cumulative (%)	
	Mass (g)	Mass (%)	Oversize	Undersize
150	8.6	1.76	1.8	98.2
106	12.7	2.60	4.4	95.6
75	14.2	2.90	7.3	92.7
38	46.7	9.54	16.8	83.2
20	83.9	17.15	33.9	66.1
-20	323.2	66.05	100.0	0.0

Table 6. Results of particle size analysis with dry and wet methods

A combination of dry and wet sieve analysis was conducted to study REE distribution in the various size fractions. The results are presented in Figure№, which shows the distribution and yield of REEs in different fractions. The results indicate +150μm size fraction having the lowest TREE concentration while -20μm size fraction having the highest TREE concentration.

As a result, REEs are more concentrated in the finer fractions. With dry and wet methods combined we can observe that most fly ash particles are below minus 20 sieve, as coarser fractions such as incomplete combustion of coal are retained in the 150-size fraction.

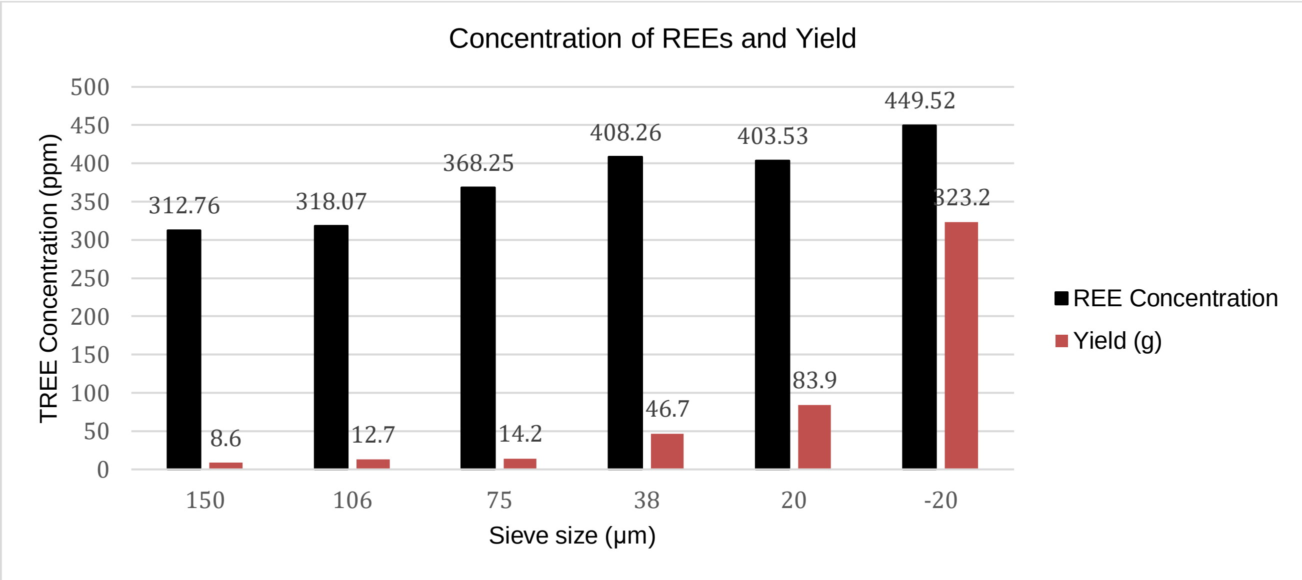


Figure 25. Concentration and Yield of REEs in different fractions

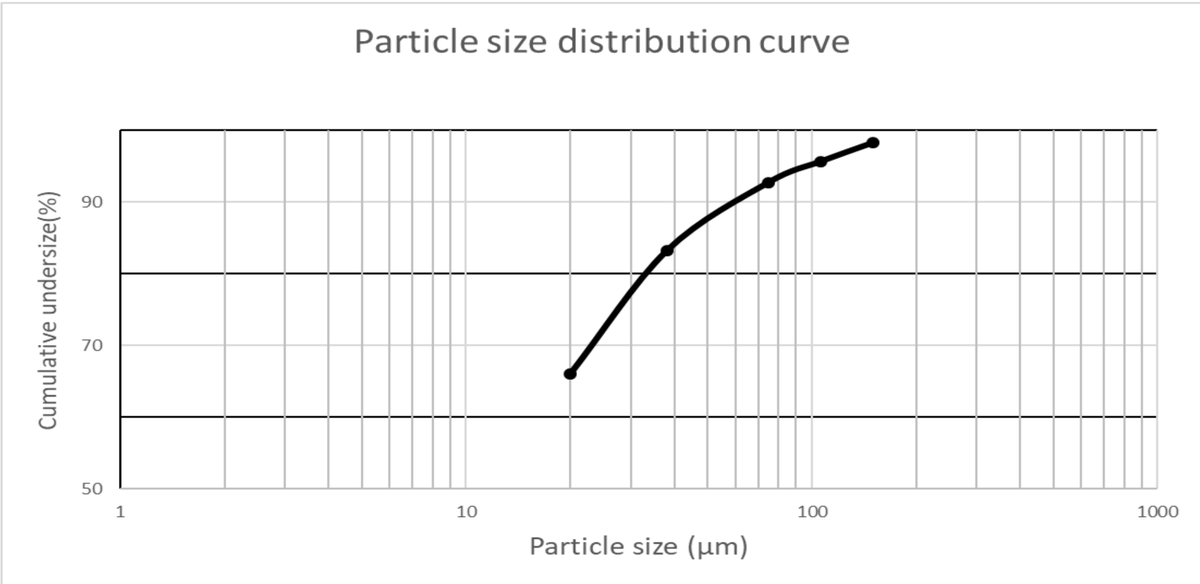


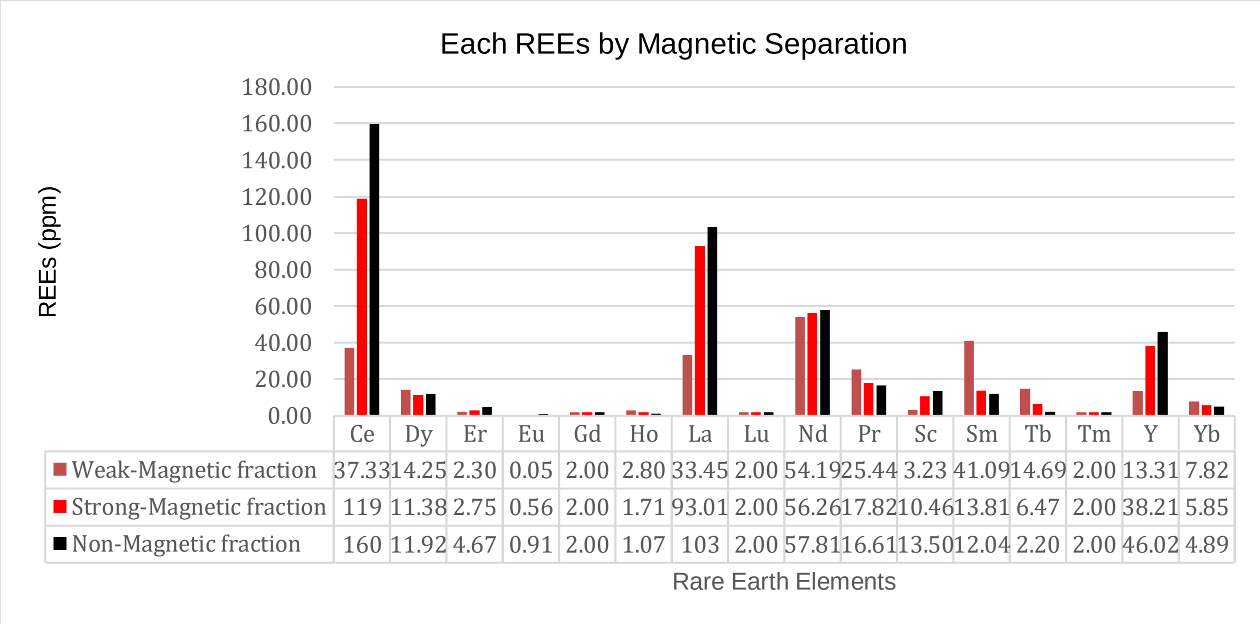
Figure 26. Particle size distribution curve

Rare Earth Elements (ppm)															
Sieve size (µm)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Er	Tm	Yb	Lu	Y	Total
150	53.58	116.8	21.3	46.01	8.62	1.25	11.53	<2	6.93	2.3	3.3	3.64	2.63	32.87	312.76
106	54.58	119	21.14	44.74	9.39	1.37	10.66	<2	7.41	2.57	3.7	3.96	2.75	34.8	318.07
75	62.75	140.2	26.66	50.64	10.81	1.39	14.37	<2	7.76	2.08	4.05	4.33	2.92	38.29	368.25
53	67.19	156.1	28.51	57.8	11.5	1.52	16.65	<2	9.11	3.06	3.76	4.79	2.75	43.52	408.26
20	67.09	150.6	29.73	58.98	10.97	1.54	17.31	<2	9.43	3.28	3.5	4.49	2.61	42	403.53
-20	77.38	171.3	30.3	62.59	11.59	1.9	19.8	<2	10.35	4.29	3.56	4.86	2.75	46.85	449.52

Table 7. Results of chemical analysis of sieve test

4.2 Summary of REEs in fly ash after a magnetic separation

Magnetic separation tests were conducted at “Central Geology Laboratory”. As for magnetic separation, different intensities of magnetic field are utilized.



	Ce	Dy	Er	Eu	Gd	Ho	La	Lu	Nd	Pr	Sc	Sm	Tb	Tm	Y	Yb
Weak-Magnetic fraction	37.33	14.25	2.30	0.05	2.00	2.80	33.45	2.00	54.19	25.44	3.23	41.09	14.69	2.00	13.31	7.82
Strong-Magnetic fraction	119	11.38	2.75	0.56	2.00	1.71	93.01	2.00	56.26	17.82	10.46	13.81	6.47	2.00	38.21	5.85
Non-Magnetic fraction	160	11.92	4.67	0.91	2.00	1.07	103	2.00	57.81	16.61	13.50	12.04	2.20	2.00	46.02	4.89

Figure 27. Magnetic Separation results by each REEs

Figure 26 shows the major REEs such as Ce, La, Nd and Y are more concentrated in the non-magnetic fractions while Sm is more concentrated in the weak-magnetic fraction due to its high magnetic susceptibility. As for Nd, which also has high magnetic properties, tends to be more associated with silicate minerals.

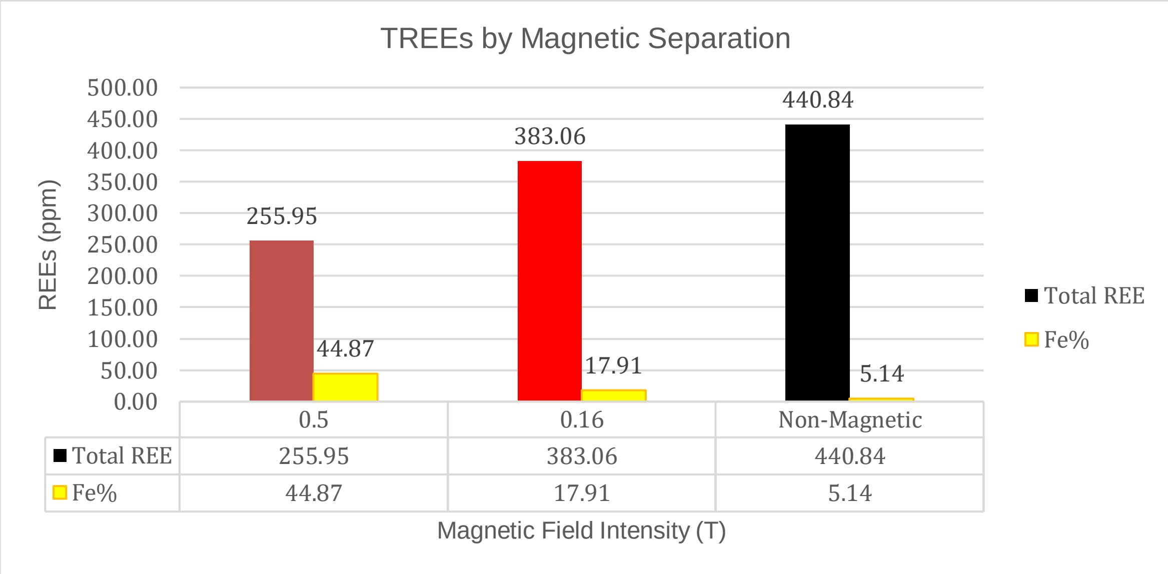


Figure 28. Total REEs and Iron grade after Magnetic Separation

Magnetic separation tests were carried out with different intensities ranging from 0.16T(weak-magnetic) to 0.5T(strong-magnetic). In the figure (№), total REE and Fe content at the applied magnetics intensities are shown. The grade of REEs increased from 249.95 ppm to 434.84 ppm in non-magnetic fraction. Most of the REEs content accumulated in the non-magnetic fractions. One probable reason for the large amount of rare earth elements (REEs) found in the nonmagnetic portion could be that most of the REE particles are linked to minerals that are not magnetic, such as quartz.

An important observation was made when analyzing the concentrate obtained at a field intensity of 0.5 T - it was found to have a high iron (Fe) content of 44.87%. Conversely, the nonmagnetic fraction had a low Fe content of 5.14%. These results indicate that by using a low magnetic field intensity, most Fe content in CFA could be removed, while improving the concentration of REE and silicate minerals in the corresponding nonmagnetic fraction.

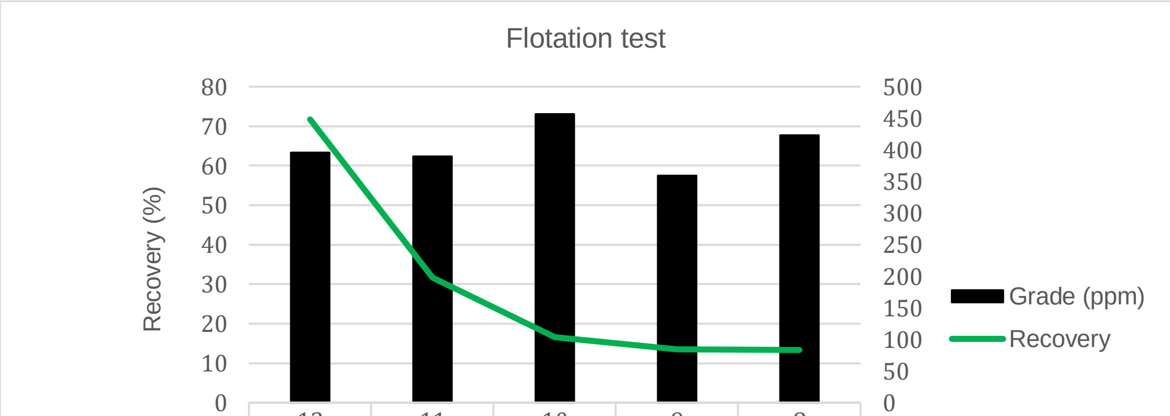
Products	Mass (g)	Yield (%)	Grade (ppm)	Recovery (%)
Weak Magnetic fraction	118.82	4.03	249.95	25.62
Strong Magnetic fraction	75	2.55	377.06	6.45
Non Magnetic fraction	2751	93.42	434.84	67.93
Feed	2944.82	100	425.91	100

Table 8. Results of Magnetic Separation

4.3 Results of flotation test

Flotation tests were performed at different pH conditions and with magnetic separation combined. The initial pulp pH was at 12 where the recovery is the most and at the pH value of 10, REEs are concentrated the most. The effects of changes in pulp pH on REE recovery and upgrade were investigated during the flotation experiments. The pulp pH decreased from the initial pulp value of 12 to 8. Concentrated HCl and diluted HCl were used as pH modifiers.

The results presented in figure 28 show that a decrease in pulp pH from 12 to 8 caused a significant decrease in REE recovery from 72% to 13%, and a corresponding increase in REE grade from 360 ppm to 456 ppm. The results suggest that the recovery and upgrade of REE from CFA is pulp pH dependent. In terms of REE recovery, the best result was achieved at pulp pH 12 while the best REE grade was achieved at pulp pH 10. Moreover, the combination of magnetic separation and flotation tests resulted in a slight increase in TREE grade from 441 ppm to 456 ppm.



pH	12	11	10	9	8
Grade (ppm)	395.98	389.83	456.44	358.72	422.85
Recovery	71.72	31.63	16.61	13.46	13.34

Figure 29. Flotation test results

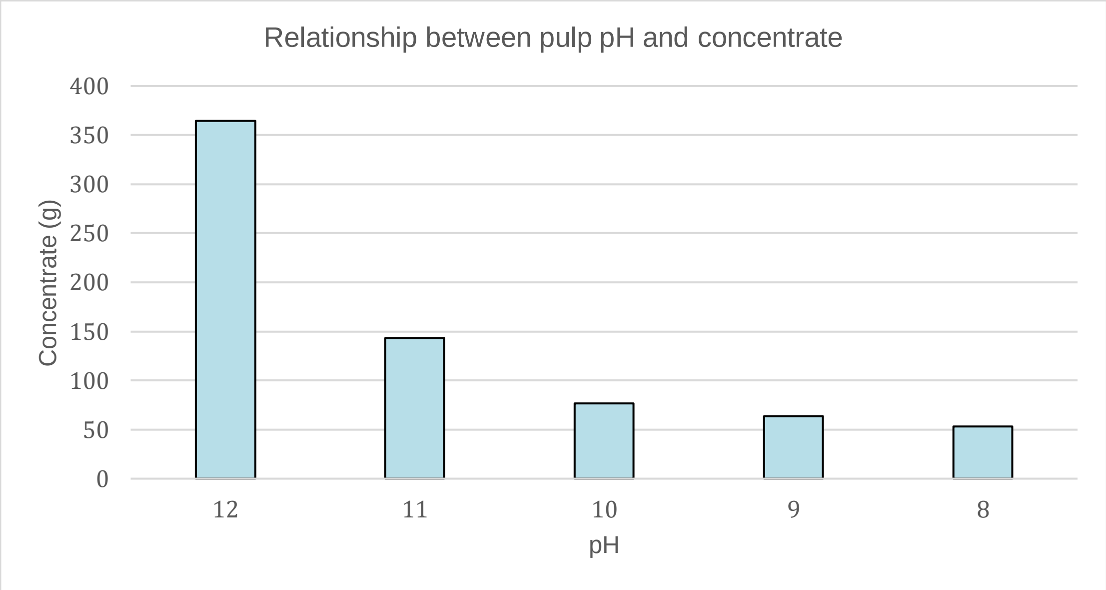


Figure 30. Relationship between pulp pH and concentrate

Figure 30 indicates the relationship between pulp pH and yield. As the pulp pH decreases the concentrate of the flotation test also decreases.

5. Conclusion

The present study has highlighted that coal-fired power plant by-products such as CFA could potentially serve as secondary sources of REEs, containing significant reserves for future beneficiation. Chemical analysis of representative CFA samples revealed that they had a total concentration of 416.7 ppm TREE, with most of the REEs concentrated in the -20μm fraction. The distribution of REEs in distinct size fractions indicated that both the coarse and fine fractions of CFA could be used for REE beneficiation.

Results from the magnetic separation tests demonstrated that reducing magnetic intensity led to a higher concentration of REEs, but the corresponding recoveries were lower. This suggests that most of the REEs were concentrated in the non-magnetic fraction, as they were more abundant in silicate minerals.

Flotation using sodium oleate produced a concentrate with a slightly higher REE grade than the tailings. The pulp's pH impacted the recovery and upgrading of REEs, with pH 12 resulting in the highest recovery and pH 10 leading to the best REEs upgrade. Lowering the pH resulted in decreased recovery. Combining magnetic and flotation processes resulted in a slightly higher REE grade at pH 10.

Overall, the study indicates that combining the methods employed in the present study could lead to enhanced REE recoveries and upgrades. Future research will investigate hydrometallurgical separation processes in addition to the methods used in this study.

6. Reference

1. Zhang J, Zhao B, Schreiner B. Separation hydrometallurgy of rare earth elements. Cham: Springer; 2016.
2. J H L Voncken. The rare earth elements: an introduction. Cham: Springer; 2016.
3. REE Supply and Demand [Internet]. Mit.edu. 2012. Available from: https://web.mit.edu/12.000/www/m2016/finalwebsite/problems/ree.html
4. Gupta CK, Krishnamurthy N. Extractive Metallurgy of Rare Earths. London: CRC Press; 2004.
5. Adriano DC, Weber J, Bolan NS, Paramasivam S, Koo BJ, Sajwan KS. Water, Air, and Soil Pollution. 2002;139(1/4):365–85.
6. Abhilash, Ata Akcil. Critical and Rare Earth Elements. CRC Press; 2019.
7. USGS Fact Sheet 076-01: Coal Combustion Products [Internet]. pubs.usgs.gov. [cited 2023 May 14]. Available from: https://pubs.usgs.gov/fs/fs076-01/fs076-01.html
8. Lima IB de, Leal Filho W. Rare earths industry: technological, economic, and environmental implications. Amsterdam, Netherlands: Elsevier; 2016.
9. Zhang W, Noble A, Yang X, Honaker R. A Comprehensive Review of Rare Earth Elements Recovery from Coal-Related Materials. Minerals. 2020 May 17;10(5):451.
10. Tang M, Zhou C, Pan J, Zhang N, Liu C, Cao S, et al. Study on extraction of rare earth elements from coal fly ash through alkali fusion – Acid leaching. Minerals Engineering. 2019 Jun; 136:36–42.
11. Honaker R, Yang X, Chandra A, Zhang W, Werner J. Hydrometallurgical Extraction of Rare Earth Elements from Coal. The Minerals, Metals & Materials Series. 2018;2309–22.
12. Abaka-Wood GB, Addai-Mensah J, Skinner W. The concentration of rare earth elements from coal fly ash. Journal of the Southern African Institute of Mining and Metallurgy. 2022 Jan 31;122(1):1–7.
13. Hidayah NN, Abidin SZ. Extraction of light, medium and heavy rare-earth elements using synergist extractants developed from ionic liquid and conventional extractants. Comptes Rendus Chimie [Internet]. 2019 Nov 1 [cited 2023 May 14];22(11):728–44. Available from: https://www.sciencedirect.com/science/article/pii/S1631074819301742
14. ICP-OES principle, ICP-OES Analysis, ICP-OES FAQ's | Agilent [Internet]. www.agilent.com. Available from: https://www.agilent.com/en/support/atomic-spectroscopy/inductively-coupled-plasma-optical-emission-spectroscopy-icp-oes/icp-oes-faq

15. Tpp4.mn. 2015 [cited 2023 May 14]. Available from: https://tpp4.mn/
16. Pan J, Nie T, Vaziri Hassas B, Rezaee M, Wen Z, Zhou C. Recovery of rare earth elements from coal fly ash by integrated physical separation and acid leaching. Chemosphere. 2020 Jun;248:126112.