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ADDIS ABABA INSTITUTE TECHNOLOGY
CENTER FOR ETHIO-MINES DEVELOPMENT (CEMD)
MASTER OF DEGREE IN MINERAL ENGINEERING

# ***EVALUATION OF FLOTATION EFFICIENCY FOR ELA - HANCHANO COAL IN THE KONTA ZONE, SOUTHWESTERN ETHIOPIA REGION, ETHIOPIA***

By

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This certifies that Mebratu Menu Decho's thesis; 'Study on *EVALUATION FLOTATION EFFICIENCY FOR ELA-HANCHANO COAL IN KONTA ZONE SOUTHWESTERN ETHIOPIA REGION, ETHIOPIA*' fulfilled a portion of the requirements for the Master of Science in Mineral Process degree at the Addis Ababa Institute Technology Center for Ethiopian Mines Development. Engineering meets the recognized standards for quality and originality while also adhering to university regulations.

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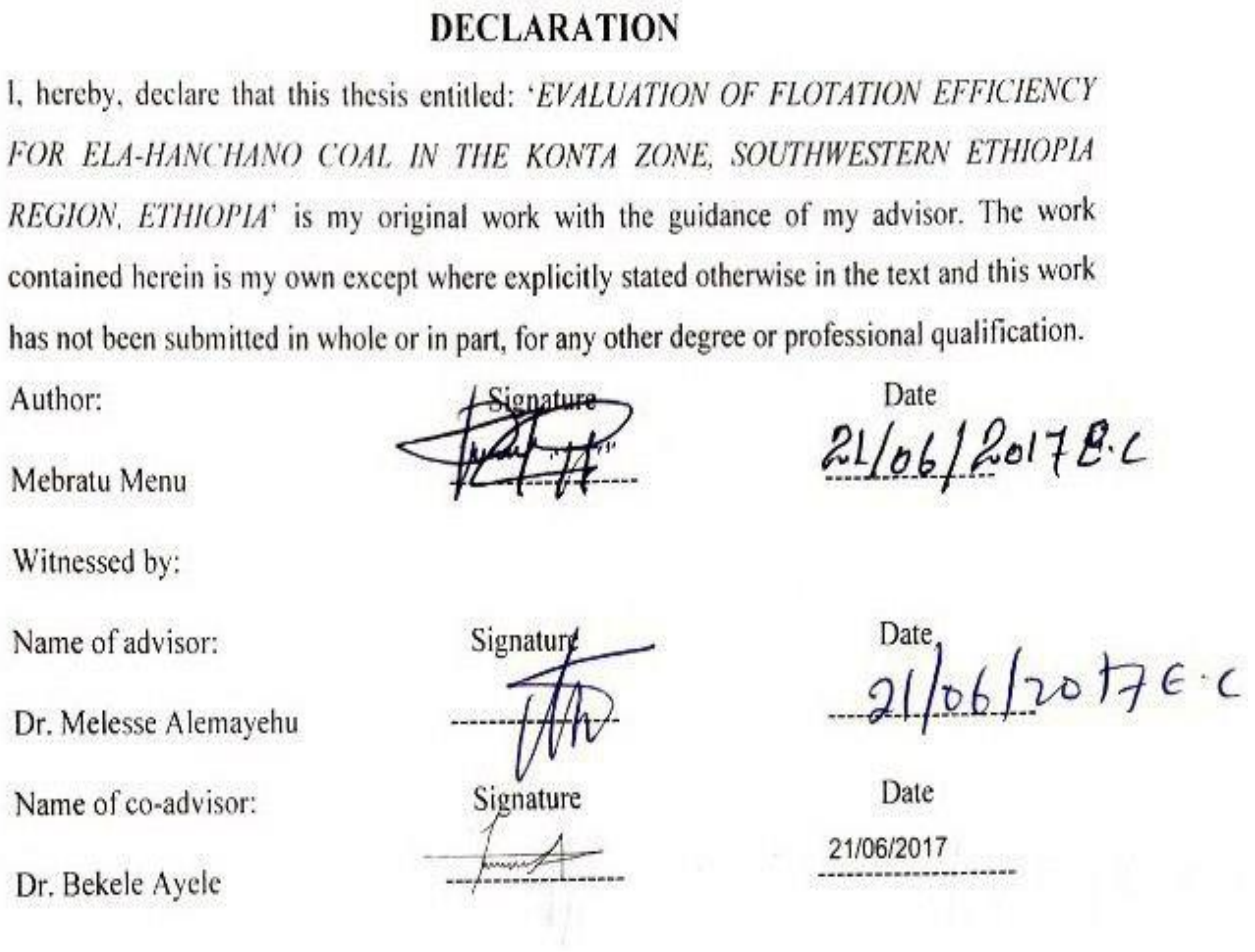
# DECLARATION



## DECLARATION

I, hereby, declare that this thesis entitled: '*EVALUATION OF FLOTATION EFFICIENCY FOR ELA-HANCHANO COAL IN THE KONTA ZONE, SOUTHWESTERN ETHIOPIA REGION, ETHIOPIA*' is my original work with the guidance of my advisor. The work contained herein is my own except where explicitly stated otherwise in the text and this work has not been submitted in whole or in part, for any other degree or professional qualification.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AAU | Addis Ababa University |
| AAiT | Addis Ababa Institution Technology |
| ASTM | American Society for Testing and Materials |
| C | Carbon |
| Cal/g | Calorie per Gram |
| CEMD | Center for Ethio-Mines Development |
| CV | Calorific-value |
| FC | Fixed Carbon |
| $g/cm^3$ | Gram per Centimeter Cubic |
| GSE | Geological Survey of Ethiopia |
| GSR | Graduation Student of Regular |
| HC | Hydrocarbon |
| MC | Moisture Content |
| NNW-SSE | North Northwest – South Southeast |
| S | Sulfur |
| SWER | Southwestern Ethiopian Region |
| µm | Micrometer |
| VM | Volatile Matter |

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# ABSTRACT

*The study focused on evaluating the efficiency of flotation processes in recovering coal from the Ela-Hanchano deposit in the Konta Zone of Southwestern Ethiopia. The work aims at improving recovery levels and upgrading the quality of coal by applying froth flotation, a physic-chemical method widely used for coal particles from associated impurities. This work considers critical parameters such as particle size distribution, the dosages of collector and frother, and their influence on flotation recovery, the grade of the concentrate, and the overall performance of coal beneficiation. Experimental work involved the preparation of coal samples through crushing and grinding, followed by sieving to the required particle size fractions (-500+250µm,-250+125µm and -75µm). Flotation tests were conducted using a laboratory flotation cell with kerosene as a collector and n-octanol as a frother. Recovery efficiency was evaluated at different reagent dosages and particle sizes. Proximate analyses were carried out to establish the physio-chemical characteristics of the treated coal, including moisture content, ash content, volatile matter, fixed carbon, sulfur content, and calorific value. Results showed that finer particle sizes significantly improved flotation recovery, and the highest efficiency was obtained as 87.58% for particles of under 75µm. The optimum collector (5ml) and frother (4ml) dosages improved the flotation process in terms of enhancing coal concentrate quality. Treated coal showed a reduction in ash content from 12.90% to 10.95%, a decrease in moisture content from 21.54% to 2.60%, and an increase in fixed carbon from 34.14% to 46.41%. The calorific value of the coal improved remarkably from 4,804.07 Cal/g (8,647.33 Btu/lb.) for raw coal and 6,418.15 Cal/g (11,552.67 Btu/lb.) for treated coal. This research underlines the importance of flotation parameters in the optimization of coal beneficiation and presents a framework that will help to improve the exploitation of Ethiopia's coal resources.*

*Keywords: Ela-Hanchano, Froth Flotation, Particle Sizes, Reagent Dosages, Recovery*

# CHAPTER ONE

# 1. INTRODUCTION

## 1.1 Background

Froth flotation is a physico-chemical process that has been widely used in the separation of fine particles based on their hydrophobic and hydrophilic properties (Drzymała & Swatek, 2007). Ancient people were aware of flotation, but it wasn't until the Industrial Revolution in the late 19th century that it was recognized as a process (Nguyen & Schulze, 2002). It has been adopted extensively in the mining industry to process low-grade ores and fine particles. The technique introduces air bubbles into slurry, which the hydrophobic particles attach to and rise to form a froth layer, leaving hydrophilic particles behind (Dube, 2019).

As a result, mining engineers and inventors wanted to develop a concentration method that could efficiently process the abundant reserves of low-grade and complex ores, which were typically challenging to extract profitably from waste rock. In 1905, the first commercially successful flotation mill was established in Broken Hill, Australia (Nguyen & Schulze, 2002). Shortly thereafter, experimental plants in Australia, Great Britain, and the United States began to report similar successes with flotation (Bunyak, 2017). Historically, this method obtained worldwide importance in the early 20th century, and since then, the application has been extended to a wide range of industrial minerals and coal. In Africa, the application of flotation techniques gained traction during the latter half of the 20th century, primarily in South Africa (Dekorte, 2015; Peatfield, 2003). South Africa, with its rich coal reserves, became a focal point for developing flotation methods to enhance the quality of coal for both domestic and export markets (Dikgwatlhe, 2016). In Ethiopia, the study and application of coal flotation is relatively recent compared to other African countries.

Coal is a critical energy resource, and its efficient utilization through mineral processing techniques such as flotation is essential for energy security (Laskowski, 2001). In Ethiopia, the study and utilization of froth flotation is relatively new, despite the country’s significant coal reserves. These reserves, particularly the Ela-Hanchano coal deposit in the Konta Zone, Southwestern Ethiopia, have the potential to contribute to the country’s energy security. However, challenges in processing and optimizing coal flotation delay the effective utilization of this resource. Understanding the parameters affecting flotation efficiency, such as particle size and reagent dosages, is crucial for enhancing coal recovery and quality. Ethiopia's main coal reserves are physiographically distributed across the NW plateau, SW plateau, and rift escarpment and are located in two different geological situations (Pre-Trap volcanic and Inter-Trappean) (Meleak, 2023). The exploration of coal deposits is crucial for energy production and industrial processes. In the Southwestern Ethiopian Region (SWER), the Ela-Hanchano coal deposit represents a significant natural resource, requiring research into optimal extraction techniques. One such technique is flotation, a mineral processing method widely used to separate valuable minerals from their ores. A popular physical-chemical separation technique in coal beneficiation is froth flotation, which separates fine coal particles from related minerals in water slurries (Liao, 2017). Flotation is a separation technique that takes advantage of differences in the hydrophobicity of materials (Ronald, 1992). Coal, due to its inherent hydrophobicity, can be efficiently separated from associated gangue minerals via flotation (Pratten et al., 1989). Understanding the factors that influence the flotation performance, including coal particle size and reagent dosage, is essential for optimizing the beneficiation process. This study aims to investigate the flotation efficiency of the Ela-Hanchano coal to optimize recovery and quality.

## 1.2 The Statement of Problem

Previous research has explored coal flotation globally, influencing factors like mineral composition, particle size distribution, and reagents used in the flotation process (Wills & Napier-Munn, 2016). However, limited research exists on Ethiopian coal, particularly the Ela-Hanchano deposit. This study aims to address these gaps by analyzing the effects of particle size distribution and reagent dosages (collector and frother) on flotation recovery and concentrate grade, providing a framework for improving coal beneficiation in Ethiopia. The Ela-Hanchano coal deposit in the Konta Zone of the Southwestern Ethiopian Region (SWER) holds significant potential as a local energy source for Ethiopia. Despite the promising coal reserves in this region, the economic viability of exploiting these deposits is limited by the lack of knowledge regarding their beneficiation characteristics, essentially their efficiency in flotation processing. Flotation is a critical mineral processing method used to separate coal from impurities, especially for fine coal particles common in deposits like Ela-Hanchano. The existing knowledge gap on the flotation efficiency of the Ela-Hanchano coal holds back the development of effective processing strategies and limits the region's ability to harness this resource for energy production.

## 1.3. Project Objective

The main objective was to evaluate the flotation efficiency of coal from the Ela Hanchano deposit to enhance recovery and product quality.

### 1.3.1. Specific Objectives

- To determine the flotation efficiency of Ela-Hanchano coal under kerosene and n-octanol dosages and evaluate its concentrations.
- To evaluate the impact of kerosene and n-octanol dosages on coal recovery and concentrate grade.
- Characterize some part of physicochemical properties of Ela-Hanchano coal.

## 1.4 Scope of the study

The scope of this study focuses on evaluating and understanding the flotation behavior of coal samples obtained from the Ela-Hanchano coal in the Konta Zone of the Southwestern Ethiopian Region (SWER) of Ethiopia considering the variables (factors) such as: particle size and collector dosage for flotation of coal concentration in the experiment.

## 1.5 Significance of the Study

- Economic Impact: This study aims to promote the use of local coal resources, potentially reducing Ethiopia's dependency on imported coal products and fostering energy self-sufficiency.
- Industrial Application: By optimizing the quality of the coal, industries such as steel, cement, and power generation can assess the feasibility of using local coal as a cost- effective energy source.
- Environmental Considerations: Understanding the sulfur content and other impurities to mitigate environmental impacts and support the development of cleaner coal utilization methods.

## 1.6 Location of the Study Area

The study site of Ela-Hanchano coal deposit is found in the newly launched Woreda Ela-Hanchano by the old name of Chida around the Gojeb River area in the Konta Zone of the Southwestern Ethiopia Region (Fig. 1). It is located around 24 km from Konta zone town Ameya, and 427 km from Addis Ababa. The 360 km road can be reached by asphalt surfaced road from Addis Ababa to Jimma, and the remaining 80 kms Jimma to Ela-Hanchano by all-weather gravel surfaced road.

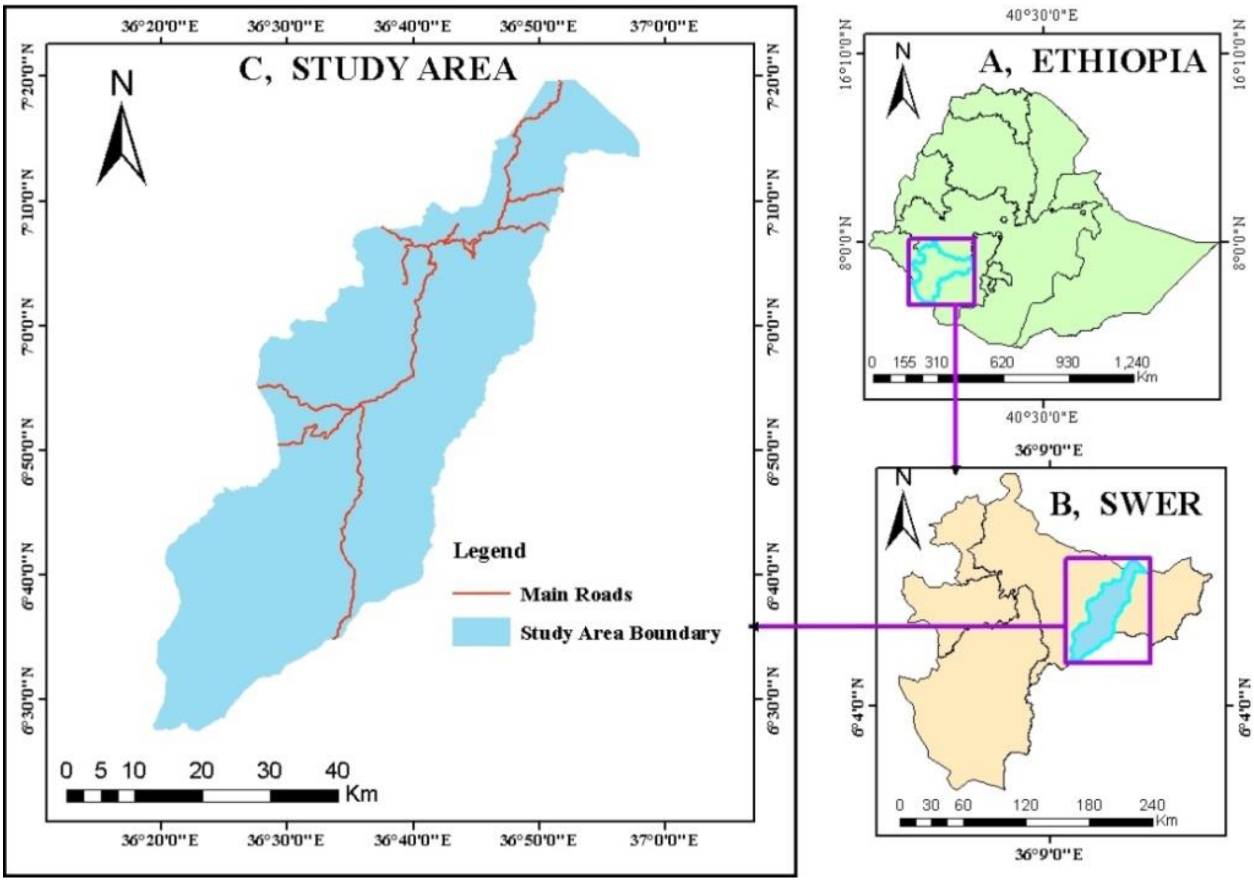


Figure 1: The Location Map of Study Area

# CHAPTER TWO

# 2. LITERATURE REVIEW

## 2.1 Froth Flotation Basics

The coal mineral physiochemical treatment requires a complex process with reagent dosages (Sokolovic & Miskovic, 2018). Froth flotation is one of the most widely used methods for physically purifying coal, which is based on the difference in surface hydrophobicity and floating ability between inorganic minerals and organic matter for fine coal purification (Meleak, 2023). The flotation of coal is primarily influenced by the hydrophobic nature of coal particles (Patnaik et al., 2020). Previous research indicates that the floatability of coal is influenced by factors like mineral composition, particle size, and reagents used in the flotation process (Wills & Napier-Munn, 2006). Froth flotation is widely used for the beneficiation of fine coal and mineral particles (Abdi, 2021). The process relies on the differences in surface hydrophobicity between particles. Hydrophobic particles attach to air bubbles and are carried to the froth layer, while hydrophilic particles remain in the liquid phase and are discarded as tailings (Drzymała & Swatek, 2007). Key reagents, such as collectors and frother, play a critical role in enhancing the separation process (Bulatovic, 2007). For coal, common collectors include kerosene, while frother like n-octanol stabilize the froth (Bulatovic, 2007).

According to Laskowski, (2001), coal's surface chemistry plays a key role in its flotation behavior, and the choice of reagents, such as collectors and frother, are critical to optimizing recovery. Coal and its associated gangue are separated by gravity in the majority of coal-cleaning procedures used to eliminate mineral impurities from coal (Ronald, et al., 1992). The density variations between pure coal particles (1.2 - 1.5) g/cm$^3$ and liberated mineral inclusions are adequate for achieving nearly total separation quite effortlessly (Keefe et al., 2013). Froth flotation is commonly employed in coal processing because of its ability to separate fine particles, which are otherwise difficult to beneficiate using gravity-based methods (Fuerstenau et al., 2007). Froth flotation is a technique widely used to clean fine coal particles by using suitable reagents that modify the surface characteristics of coal, making them hydrophobic (water-repellent) (Kalyani et al., 2005). This hydrophobic property enables the coal particles to attach to air bubbles in the flotation cell rise to the surface and form a froth layer. The unwanted hydrophilic (water-attracting) materials remain in the water causing them to detach from the targeted coal particles (Kumar & Sivrikaya, 2021). A Mechanical flotation cell is widely used equipment in mineral processing, designed to separate hydrophobic materials from hydrophilic ones. The flotation process involves the following key components and mechanisms as shown (Figure 2)

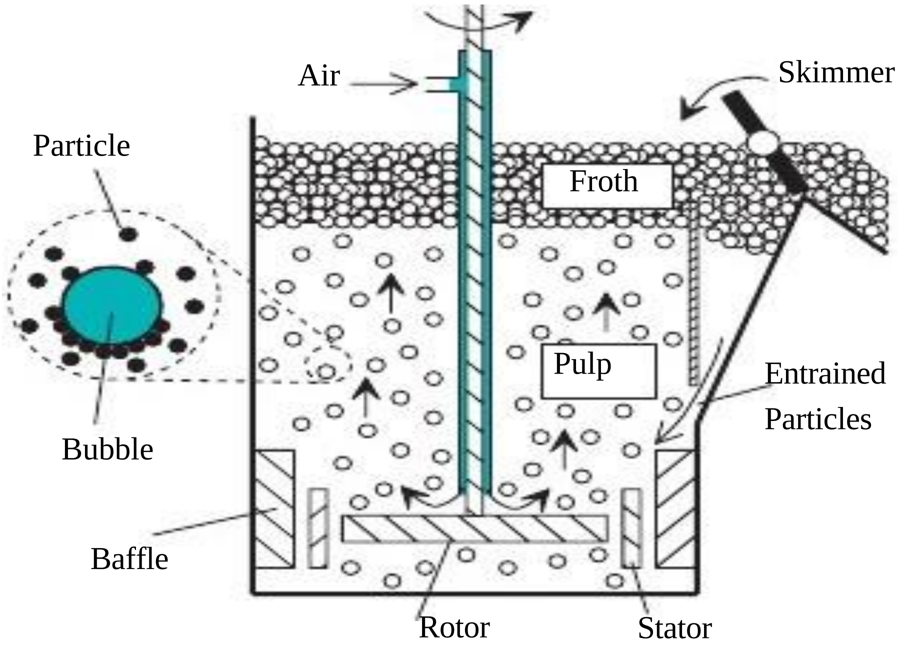


Figure 2 :The working mechanism of a standard mechanical flotation cell(Nguyen & Schulze, 2002)

According to Fuerstenau (2003), shown in Table 1 looks at the different types of minerals with respect to their contact angles, which reveal their ability to resist water and attach to air bubbles during flotation. Minerals with higher contact angles, such as graphite, sulfur, and talc, exhibit strong hydrophobic properties, making them more likely to float without additional chemical treatment. In contrast, some minerals such as coal have just average floatability, depending on the impurities present and their makeup. The efficiency of flotation depends a great deal on the contact angle. The higher the angle, the more bubble attachments happen, and the recovery rate is improved. For those minerals that have low natural hydrophobic traits, collectors are used to change their surface nature to improve flotation. Such understanding is critical in determining the right reagents to use and optimizing conditions for flotation to effectively separate useful materials.

Table 1: Naturally hydrophobic minerals and their respective contact angles (Fuerstenau, 2003)

| **Minerals** | **Compositions** | **Contact Angle by Degree** |
|---|---|---|
| Graphite | C | 86 |
| Coal | Complex HC | 20 - 60 |
| Sulfur | S | 85 |
| Molybdenite | $MoS_2$ | 75 |
| Stibnite | $Sb_2S_3$ | - |
| Pyrophyllite | $Al_2(Si_4O_{10})(OH)_2$ | - |
| Talc | $Mg_3(Si_4O_{10})(OH)_2$ | 88 |
| Iodyrite | Agl | 20 |

## 2.2 **Flotation Techniques**

The most crucial component of the flotation process is the reagent (Bulatovic, 2007). Particles to be floated must selectively attach to air bubbles, so they must be hydrophobic. A few minerals like sulfur are naturally hydrophobic, so they can be floated directly, but most minerals are hydrophilic (like pyrite, galena, and chalcopyrite) have to be hydrophobic by adding selected surface-active chemicals called collectors (Fuerstenau, 2003). The froth flotation process relies on the surface properties of solids which are influenced by various regulating agents. The reagents utilized in flotation can be categorized into the following groups: collector and frother. Although the surface of coal is generally hydrophobic a variety of chemicals are employed in coal flotation to improve process efficiency and the float ability of coal particles (Dube, 2019). The type, consumption, dosing point, and dosing mode of the reagents used in the flotation process are referred to as the reagent system, also known as the flotation reagent scheme (Bulatovic, 2007). The reagent system is an essential part of the overall flotation performance and indices (Ronald, 1992). Mineral selectivity tests on the ore are necessary to identify the type and quantity of reagents. For efficiency and effectiveness the number of dosing points, their locations and the dosing technique must all be continuously optimized in practice (Jiangxi, 2024). Surfactants, specifically collectors and frothers, are introduced to enhance the hydrophobic properties of minerals. This addition facilitates the selective adsorption of the collector and mitigates the interference in flotation processes caused by various dissolved or colloidal substances (Fuerstenau, 2003).

### 2.2.1 Collector Parameter

A sizable class of organic chemical compounds with varying chemical compositions and functions are known as collectors. The collector's primary function is to create a hydrophobic layer on a specific mineral surface in the flotation pulp in selective manner. This creates the ideal environment for the hydrophobic particles to adhere to air bubbles and be recovered in the froth product (Bulatovic, 2007). One of the most popular collectors in coal flotation facilities is kerosene (Cheng et al., 2020). To achieve both selective adsorption and hydrophobicity, a collector molecule must have two key functional components: a nonpolar group that provides sufficient hydrophobicity and a polar or ionic group that interacts electrostatically or chemically with the mineral surface species (Fuerstenau, 2003). Most minerals need to be made hydrophobic in order to float. This is accomplished by adding surfactants called collectors to the pulp and allowing adsorption to occur during agitation, a process known as the conditioning period. By adsorbing molecules or ions onto the mineral surface collector's organic compounds make certain minerals water-repellent. This lowers the stability of the hydrated layer that separates the mineral surface from the air bubble to the point where a particle can attach to the bubble upon contact (Wills & Napier-Munn, 2006).

### 2.2.2 Frother Parameter

Frother is heteropolar surface-active substances that can adsorb on the air bubble–water interface and reduce the surface tension of water. Their presence in the liquid phase strengthens the air bubbles' layer, which improves the hydrophobic particles' ability to adhere to the bubbles (Bulatovic, 2007). The bubbles ascending to the surface of the flotation cell should remain intact until they are skimmed off for the collection of the floated particles (Fuerstenau, 2003). Frother are introduced to stabilize bubble formation in the pulp phase, ensuring a sufficiently stable froth that allows for the selective drainage of entrained gangue, while also enhancing flotation kinetics (Farrokhpay,2011). Froth stability is a crucial factor affecting flotation performance, particularly in coal flotation. Stable froths tend to retain more valuable coal particles, leading to improved recovery, but excessively stable froths can hinder gangue removal, affecting the purity of the concentrate (Dickinson et al.,2004).

## 2.3. Factors Affecting Froth Flotation

Froth stability depends on the type and concentration of the frother, as well as the nature and concentration of the particles present in the system (Farrokhpay, 2011; Pugh, 2016). Numerous factors affect the stability of foam, which is mainly related to the drainage of liquid within the foam and the rupture of the liquid films therein (Dickinson et al., 2004). However, the concentration and type of frother used can significantly change the froth properties (Glenn&Goldman,1976). Jiangxi (2024) asserts that flotation efficiency and recovery are impacted by both large ore particles (more than 0.1 mm) and small ore particles (less than 0.006 mm). Because of their hefty weight, flotation coarse particles are difficult to suspend in the flotation machine and have a lower likelihood of colliding with the bubbles. Furthermore, the high dropout force makes it simple for the coarse particles to separate from the air bubbles once they have adhered to them.

### 2.3.1. Coal Particle Size Distribution

The distribution of particle size is a major importance in mineral processing. The behavior of particles in crushing and grinding circuits, concentration operations, and solid-liquid separations is strongly dependent on size (Fuerstenau, 2003). Because it influences reagent adsorption, bubble size distribution and air holdup, gas bubble mineralization and the stability of bubble-particle aggregates (as shown by particle attachment and detachment rates) particle size is a crucial flotation process component (Sobota & Bedeković, 2024). Particles of various sizes behave differently in flotation system directly affecting flotation recovery and overall performance (Sokolovic & Miskovic, 2018). The foam is more likely to be stabilized by fine particles than the coarser ones. The large mass of coarse particles causes them to detach from bubbles due to gravitational forces. Accordingly (Patnaik et al.,2020) for coarse particles to avoid separation, they need to be more hydrophobic have smaller bubbles and have controlled turbulence. Small bubbles high collector concentrations and extended residences are necessary for fine particles to improve flotation (Liao, 2017). When the contact angle surpassed a specific value referred to as the critical contact angle flotation was observed. The particle size is inversely related to the critical contact angle (Norori-McCormac et al., 2017). In contrast to finer particles, coarser particles have a smaller critical contact angle. The more hydrophobic a particle is the more likely it is to adhere to a bubble; this results in a high contact angle between the particle and the bubble and a notable rise in flotation (Achaye et al.,2021). Small bubbles high collector concentrations and extended residence durations are necessary for fine particles to improve flotation. This is due to the fact that finer particles can create a denser froth structure which lowers drainage rates. On the other hand, the froth may be disturbed by coarse particles, which would accelerate its.

### 2.3.2 Reagent Dosages

Without reagents, flotation would not occur and without flotation, the modern mining industry would not exist (Khoshdast, 2011).The main factor influencing the separation of minerals using froth flotation techniques is the variation in particle wettability. Coal flotation efficiency, recovery and product quality are directly impacted by the quantity of chemicals utilized. The type and concentration of collectors and frother significantly influence recovery and grade. Proper optimization is necessary to achieve the desired flotation performance. Collectors and frother are the primary reagent types utilized to regulate various process elements. In order for coal particles to adhere to air bubbles, collectors like diesel, kerosene, and fuel oil assist make them more hydrophobic. Insufficient hydrophobicity of the particles results in poor coal recovery when the collector dose is too low. But too much collector dose can cause too much frothing and more undesirable elements, like ash, to be entrained. Achieving the ideal balance preserves product quality while ensuring a strong recovery. When the dosage of the frother is too low, the bubbles get too big, which makes it harder for coal particles to stick to them (Cho & Laskowski, 2002). Conversely, too much frother produces too much froth, which causes gangue minerals and fine ash to unintentionally entrain. The formation of steady, tiny bubbles that improve coal recovery without adding too many pollutants is facilitated by a well-optimized frother dosage. Optimizing reagent dosage is essential to achieving the best flotation performance. A well-balanced approach ensures high recovery, improved selectivity, and lower chemical costs.

## 2.4. Geology of coal

According to Thomas, (2013) coal is a distinct type of rock in the geological record characterized by a broad spectrum of chemical and physical properties and has been the subject of extensive study over time. The key periods of coal formation in the geological timeline, such as the Carboniferous, Cretaceous, Paleogene, and Neogene (often collectively referred to as the Tertiary) are discussed along with major coal deposits around the world. The fossilized remains of plants that grew millions of years ago, ranging from tropical to subarctic, make up coal. The vegetation, which includes grass, algae, spores, tree trunks, roots, branches, leaves, and a combination of all plant elements, gathered in marshy conditions before being covered by sediments from rivers or oceans that eventually filled in sinking basins (Peter D. Warwick, 2019). Coals are created when vegetable waste builds up in a specific deposition environment. The coal rank and different levels of structural complexity are determined by syn-sedimentary and post-sedimentary forces that have an impact on such accumulations (Han Dexin, 1996). The chemical makeup, rank, and geological origin of coal impact its behavior in flotation. According to (Jovanovski et al., 2023) The term "humic coals" refers to coals that formed from mostly woody and/or reed/sedge residues through peatification processes, which mostly take place in the moderately wet aerobic zone of mire (humification). As a result they usually originate mainly from wood or peat that is rich in reeds and sedges and then mostly from thin layers of organic mud. On a macroscopic level, humic coals can be banded with vitrain layers alternating with other lithotypes or vitrains or bright clarains. They include duroclarite, inertite, vitrite, clarite, and vitrinertite by microlithotype. The predominant maceral percentage composition is either vitrinite or inertinite, particularly fusinite and semifusinite. Typically humic coals are dark brown to black in color and fracture in the banding and cleat planes (O’Keefe et al.,2013).

### 2.4.1. Coal Formation

Coal is formed from the accumulation of plant material, typically in a swamp environment. When plants die and fall into the swamp the stagnant water helps prevent their decay. Swamp waters are generally low in oxygen which would otherwise react with the plant material and lead to decomposition. This oxygen deficiency allows the plant debris to remain intact (Subba Rao, 2016). According to Osborne, (1988), coal is the general descriptive term applied to a group of solid fossil fuels, black or brown in color, that consist predominantly of altered plant material and usually occur as seams within other consolidated strata (Curtis Wrew Mohns, 1997). Coal is formed from the biological decay of plant material in a favorable environment followed by chemical and physical conversion into coal. Biochemical factors play an important part in the first stage of the coalification process. High temperatures enhance the degree of coalification and the rate of conversion. Generally, coalification proceeds as a continuous transformation of plant material with each phase characterized by a certain measure of the degree of coalification. The rank generally increases with the following groups: peats, brown coals, lignite, subbituminous, bituminous, and anthracites. Plants that grew in and around wetlands in warm, humid areas hundreds of millions of years ago are generally believed to be the source of the majority of coal (as well as the other two fossil fuels, oil and natural gas) that are currently extracted (Jovanovski et al., 2023). There are three main sources of evidence that coal was derived from plants (Jovanovski et al., 2023).

- The first has to do with lignite, which is the lowest rank of coal and frequently contains identifiable plant fragments.
- The second piece of evidence is the presence of plant fossils (leaves and stems) in the form of imprints and burned films in sedimentary rock layers above, below, and next to coal seams.
- The final piece of evidence pertains to the possibility of plant precursor material present in even high rank coal.

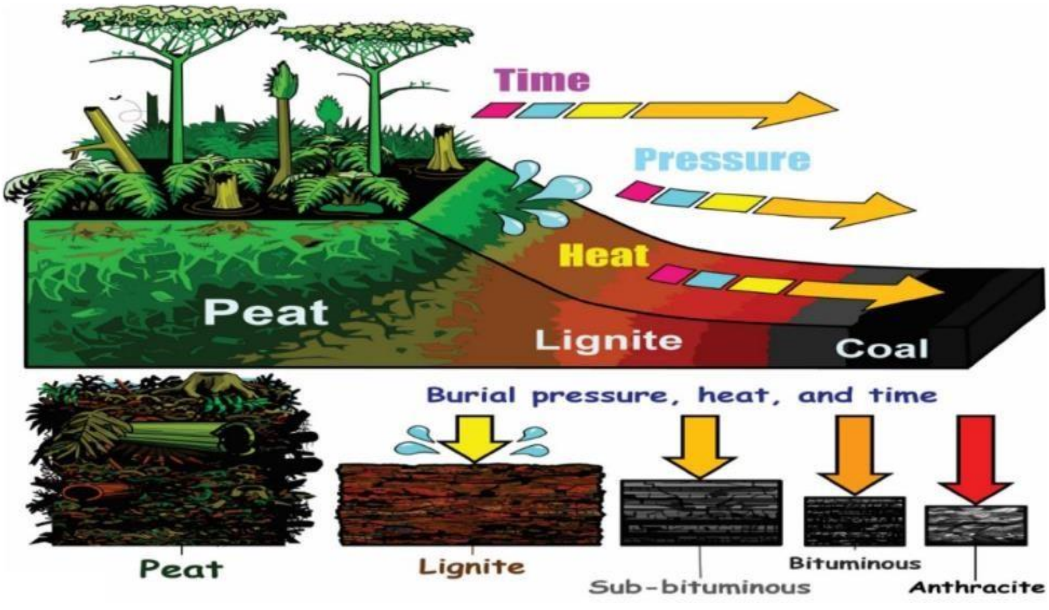


Figure 3: Formation of Coal (Jovanovski et al., 2023)

According to (Thomas,2013), Coalification is the alteration of vegetation to form peat, succeeded by the transformation of peat through lignite, subbituminous, bituminous, semi- anthracite to anthracite and meta-anthracite coal. Coals are divided into four categories based on chemical parameters: bituminous, anthracite, lignite, and peat. This classification is based on the amount of moisture, ash, and carbon. The initial stage of the development of all coal kinds is called peat. It is a collection of unique organic components that have partially decomposed and are mostly generated from plant wood. Its color varies from light brown to dark brown (Warwick, 2005; Thomas, 2013). Peat is not essentially coal. It is a buildup of organic matter or partially decomposed plants and represents the initial stage of transformation. Peat develops in wetland environments when floods or standing water impede the atmospheric flow of oxygen, delaying the rate of decomposition. Peat contains less than 40 to 55 percent carbon, sufficient volatile matter, a lot of moisture, and impurities (Thomas, 1992). **Lignite**, commonly referred to as brown coal or rosebud coal, is a type of coal characterized by its relatively low carbon content and high moisture levels. It is regarded as the lowest coal rank. The texture and color of lignite harden and darken with age. The newly introduced product is referred to as sub-bituminous coal (Chen, p. 2018). It is also called ‘brown coal’ because of its characteristic brown color. It is generally woody in nature. It has high moisture content (between 25 and 45 percent). Because of its comparatively low heat content, it is regarded as the lowest rank of coal.

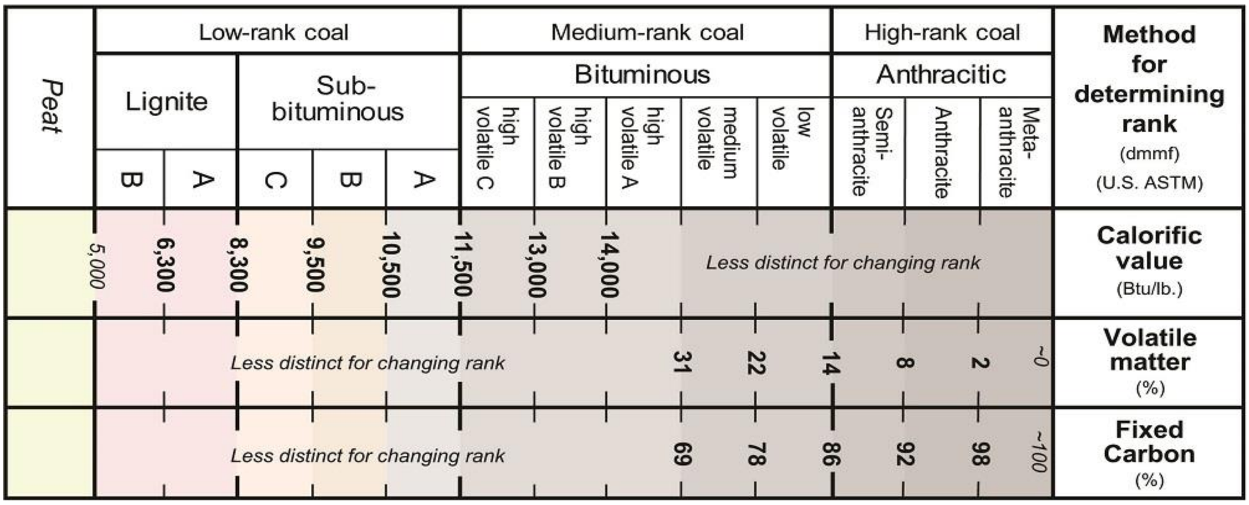
**Sub-bituminous**: is a black, dull coal in the middle grade between bituminous and lignite coal. It is practically free of woody matter or plant materials (Thomas, 2013). **Bituminous:** The most accessible and utilized type of coal is bituminous coal, sometimes known as black coal. They have a carbon content of 69% to 86% and lower moisture and volatile content than lignite coals, ranging from 5% to 45% (Voncken, 2020). Their high volatile content and high heating value make them easily combustible when ground into powder, and their flame lasts a long time. These coals are dense and compact and possess very high calorific value (Chen, 2018;Voncken,2020).They are utilized in the manufacturing of coke and gas. In terms of geology, bituminous coals are found all over the world and date from the Carboniferous to the Cretaceous periods. **Anthracite:** A high-rank coal is anthracite, which means that it has undergone the highest level of metamorphism. Anthracite is shiny black, hard, and brittle and has the highest fixed-carbon content (approximately 86 to 98%) (Thomas, 2013). Anthracite burns slowly because of its low volatile matter content (2–12%). It is a hard coal with jet black color and semi-metallic luster (Jovanovski et al., 2023). It has a high heating value.

### 2.4.2. Coal Rank Classification

Numerous classification systems have been developed to group coals into ranks of these; the American Society for Testing and Materials (ASTM) system has gained the coal acceptance and is exclusively used in North America. According to Qian Zhu, (2014), these standards play a crucial role in testing and analyzing coal, coke, natural gas, other gaseous fuels, and the combustion residues of coal and coke. Additionally, these standards are extensively employed in universities and research labs for academic research on coal and the development of new analytical methods. The thermo-physical property tables for methane, ethane, propane, regular butane, and isobutene are also included in these standards. These standards enable laboratories and other chemical facilities to investigate and evaluate these fuels in order to guarantee their safe use and handling (Qian Zhu, 2014). For classification, the American Society for Testing and Materials (A.S.T.M.) employs the fixed for low-rank coals with high moisture content, the calorific value of the moist, mineral matter-free coal is higher than that of high-rank coals, which include carbon or volatile matter (Speight, 2005). There are several classifications and divisions into which the coals are divided. Coals that rank higher than high-volatile coals (B) Coals classified as bituminous, or having less than 31% volatile matter on a dry mineral matter-free basis, are categorized based on their fixed carbon levels (Committee, 2013). In dry mineral matter-free coals with more than 31% volatile matter are categorized based on their "moist calorific value. “Moist calorific value, or moist B.T.U., is the calorific value of coal that includes its natural bed moisture but excludes water that is visible on the coal's surface (Hower et al., 2022). The scheme of ASTM classification is given in the following Tables (2&3). According to (Jovanovski et al., 2023) the classification of coals by their degree of progressive alteration due to increasing heat and pressure from peat, through lignite, sub-bituminous, bituminous coal and anthracite. Whereas specific categories and parameters may vary among countries, the general upward sequence in the coal ranks and its applications are shown in Table 3 and Table 4, respectively.

Table 2: General Coal ranks with their applications (Qian Zhu, 2014)

| Coal Rank | Carbon Content (%) | Heat value (BTUs-per pound) | Application |
|---|---|---|---|
| Anthracite | 86-98 | 15,000 | Home heating |
| Bituminous | 45-86 | 10,500 to 15,500 | Generate electricity and make coke for the steel industry, supplying heat for industrial processes |
| Sub-bituminous | 35-45 | 8,300 to 13,000 | Cleaner burning |
| Lignite | <35 | <8,300 | Coking |



| Peat | Low-rank coal | | | | | Medium-rank coal | | | | | High-rank coal | | | Method for determining rank (dmmf) (U.S. ASTM) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lignite | | Sub-bituminous | | | Bituminous | | | | | Anthracitic | | | |
| | B | A | C | B | A | high volatile C | high volatile B | high volatile A | medium volatile | low volatile | Semi-anthracite | Anthracite | Meta-anthracite | |
| | *5,000* | 6,300 | 8,300 | 9,500 | 10,500 | 11,500 | 13,000 | 14,000 | *Less distinct for changing rank* | | | | | Calorific value (Btu/lb.) |
| | *Less distinct for changing rank* | | | | | | | | 31 | 22 | 14 | 8 | 2<br>~0 | Volatile matter (%) |
| | *Less distinct for changing rank* | | | | | | | | 69 | 78 | 86 | 92 | 98<br>~100 | Fixed Carbon (%) |

Table 3:U.S. coal rank system showing the parameters used to define ranks (Coal Rank, Kentucky Geological Survey, University of Kentucky.)

### 2.4.3 Ethiopian coal deposits

Source potential of the country includes several hundred million tons of coal and oil shale, and over 70 billion cubic meters of natural gas (Eastern Africa Resource Base, 2007). The Southwestern plateau is one of the areas that have structural evidence of the extension of East African Rift System to South part. The structural evolution of western arm of the African Rift System has impact on the Gojeb-Chida coal bearing basins (Ministry of Mines and Energy, 1995). In the Western part of the country Triassic, Jurassic, and Cretaceous sediments are usually overlain by tertiary basaltic lava flow and pyroclastics, which erupted from the rift faulted zones. The structural evolution of western arm of the African Rift System has an impact on the Gojeb-Chida coal bearing basins (Ministry of Mines and Energy, 1995). Several smaller and isolated basins including the Chida basins are part of these tectonic features. The orientation of these basins follows NNE-SSW directions (Ministry of Mines and Energy, 1993). A variety of natural resources, including coal, geothermal energy, and natural gas, are abundant in Ethiopia. Coal, which is found in Ethiopia, is a Cenozoic rock that is linked to lacustrine sedimentary rocks (Cheepurupalli et al., 2019). According to Wolela, (2007), the distribution of coal in different regions of the nation ensures greater coal reserves, which act as a link between the expansion of industry and the sustainable use of coal reserves in the future energy generations. Ethiopia is known to have two different kinds of sedimentary successions that contain coal. The facies can be categorized into two groups: (i) those comprising shale, coal, and sandstone; and (ii) those consisting of siltstone/mudstone, coal, and shale. In contrast to the siltstone/mudstone-coal-shale facies, the coal seams found within the sandstone-coal-shale facies exhibit greater thickness and a more enduring presence. The presence and distribution of coal in many Ethiopian regions, including the Mush Valley Basin, Jiren, Delbi-Moye, Lalo-Sapo, Chida, Chilga, Nejo, and Wuchale are shown Table 4. The geological settings of Ethiopia's are two types of coal resources: inter-trap and pre-trap (Fig.4;Wolela, 2007).

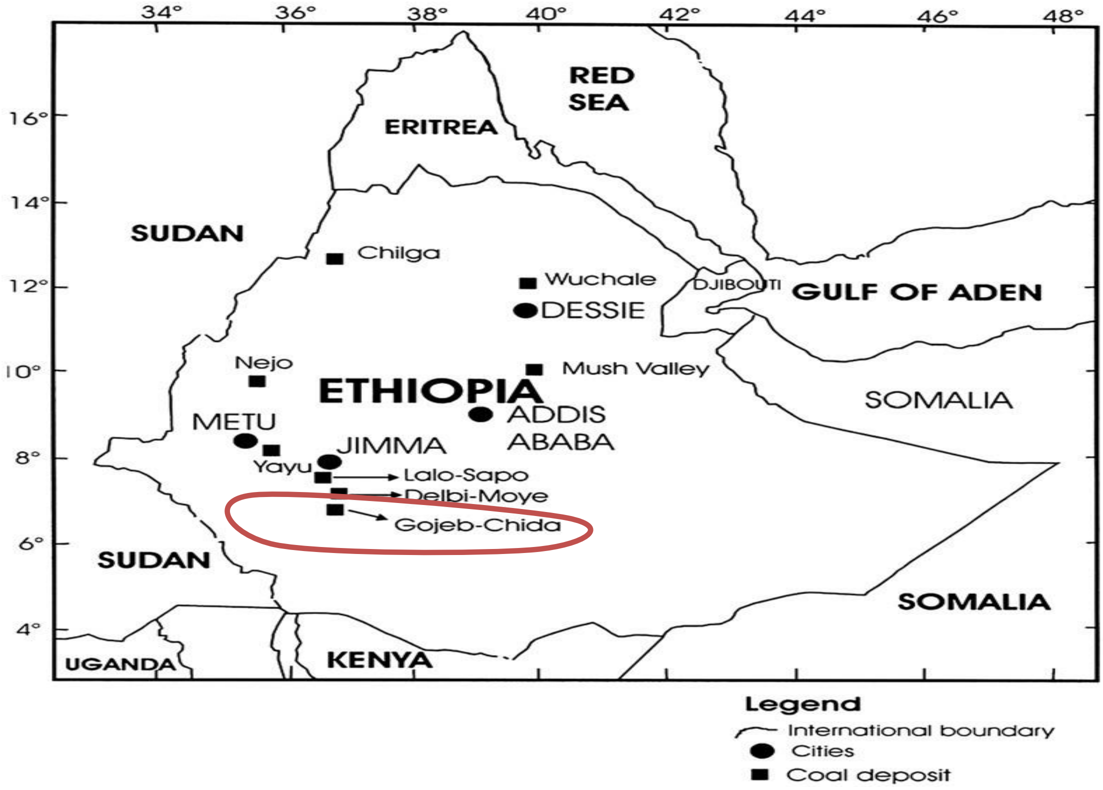


Figure 4: Maps showing the locations and distribution of coal deposits in Ethiopia(Wolela, 2007).

The Gojeb-Chida basin is located between the latitudes of 7°10' and 7°19' N and longitudes of 36°45' and 36°53' E in Konta zone of the Ela-Hanchano Woreda Southwestern Ethiopia Region (Wolela, 2008). The Gojeb-Chida Basin contains deposits of both coal and oil shale’s. The formation of the Chida Basin is associated with a fault system that trends in a NNW-SSE direction (Wolela, 2008). The basin consists of trapped volcanic and sedimentary rocks, with sedimentation taking place on a basaltic substratum that is subsequently overlaid by younger volcanic layers. The sediments are mainly made up of terrigenous, biogenic, and volcanogenic materials (Wolela, 2005). Sedimentation in the basin is characterized by fluvio-lacustrine depositional environments (Genetu & Kebede, 2024). The coal-bearing sediments in the Chida Basin reach a maximum thickness of 60 meters, with coal seams up to 2.5 meters thick. These coal-bearing sediments extend over an area of 4 square kilometers, with an estimated reserve of 9,500,000 tons of lignite to sub-bituminous (Wolela, 2008). The pre-rift tertiary volcanic series includes two major lithology units, i.e., basalt and the over laying trachyte rocks. A large portion of the studied area is covered by soil (residual silty clay, deluvial, colluvial, and rarely alluvial soils that cover almost all parts of the volcanic materials. The sedimentary units include sandstone, coal, and other associated sediments (volcano-clastic sediments, carbonaceous mudstone, mudstone, oil shale, and clay stone) that are overlaid by basalt (aphanetic) and, in some places, directly overlaid by the Trachyte unit.

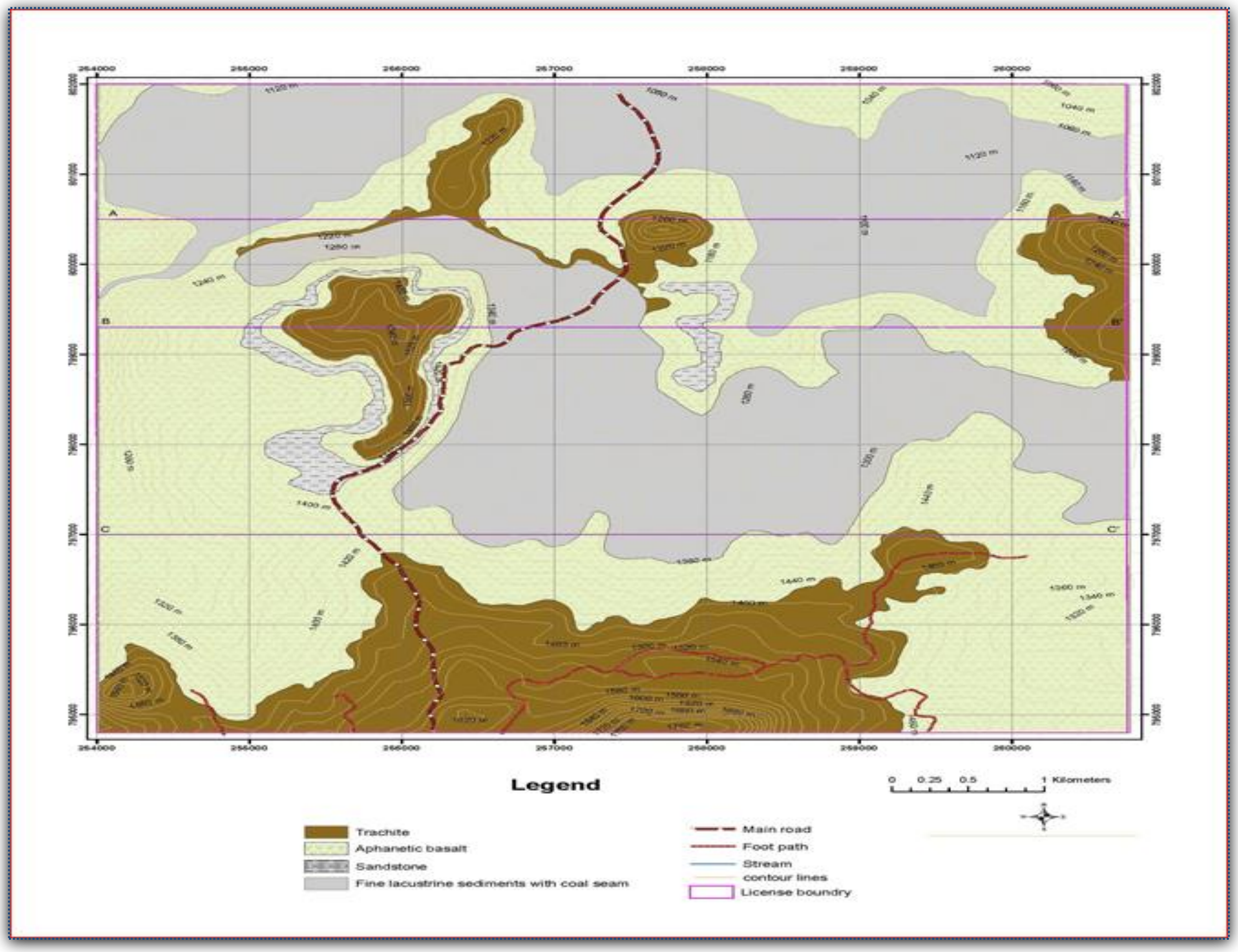


Figure 5: The geological map of study area (Source: Kripto Mining and Chemicals plc)

According to (Wolela, 2008), the humic coals in Yayu, Chida, Mush Valley, Nejo and Wuchale Basins range in ash content (16.6-41.6 %), fixed carbon (10.6-45.2 %), volatile matter (18-40.6 %) and calorific values (2824.5-4599.5 cal/g) (Table 4). These coals are categorized as bituminous to lignite coals with low to medium ash concentration, medium volatile matter, and moderate calorific values. Below in the Table-4 the shaded or colorized part are the study area of geological data collected from an outcrop near the Gojeb River, specifically in an area called by the updated name of Ela-Hanchano, however the previous name was Chida. The numbers listed represent various measurements, likely related to the composition or characteristics of the coal, such as mineral content, physical and chemical properties. The values which indicate different parameters measured at this site, while the "9 x $10^6$" might represent a specific quantity, like the volume of material concentration measurement. .

Table 4: Proximate analysis and calorific values of Ethiopian coal deposits in different basins (Wolela, 2007)

| **Basin** | **Locality** | **Depth ( m)** | **Thickness(m)** | **Moisture (%)** | **Volatile-matter (%)** | **Fixed carbon (%)** | **Ash (%)** | **Calorific-value (Cal/g)** | **Reserve (tone)** |
|---|---|---|---|---|---|---|---|---|---|
| Delbi- Moye (Eastern block) | Legamese Stream | Outcrop | 1.0 | 8.58 | 29.0 | 49.1 | 11.9 | 6495 | 20 x10$^{6}$ |
| | BH-1 | 64 | 2.0 | 5.7 | 25.9 | 42.8 | 25.7 | 6420 | |
| | | 90.7 | 1.8 | 3.8 | 27.7 | 58.1 | 11.2 | 6350 | |
| | BH-2 | 50.8 | 1.4 | 4.0 | 26.3 | 47.1 | 22.7 | 2520 | |
| Yayu (Wittete Block) | Teble Stream | Outcrop | 4.0 | 18.6 | 28.3 | 28.1 | 24.6 | 3795 | 200 x 10$^{6}$ |
| | BH-2-1 | 90.8 | 1.54 | 8.1 | 44.9 | 14.5 | 42.1 | 5605 | |
| | BH-10-1 | 78 | 2.1 | 10.9 | 46.5 | 11.3 | 42.2 | 5930 | |
| | BH-7-2 | 119 | 1.9 | 20.7 | 42.0 | 16.0 | 41.9 | 5430 | |
| Lalo-Sapo | Bokai Stream | Outcrop | 2.0 | 13.4 | 32.4 | 20.9 | 33.1 | 4120 | 7.5 x 10$^{6}$ |
| | Waro Stream | Outcrop | 1.0 | 12.0 | 18.2 | 58.3 | 11.5 | 4015 | |
| | Geta Stream | | 0.7 | 9.1 | 20.5 | 52.4 | 18.1 | 2626 | |
| Chida | Near Gojeb River | Outcrop | 1.0 | 11.2 | 15.0 | 51.0 | 22.8 | 2492 | 9 x 10$^{6}$ |
| | | | 1.5 | 18.9 | 27.6 | 22.4 | 33.5 | 4333 | |
| | | | 0.9 | 13.5 | 29.5 | 19.6 | 37.3 | 4088 | |
| Mush Valley | Mush River | Outcrop | 1.8 | 21.3 | 31.8 | 27.9 | 19.0 | 2824 | 1 x 106 |
| | | | | 21.4 | 40.4 | 10.6 | 27.6 | 3568 | |
| Nejo | Mecakani | Outcrop | 0.5 | 16.0 | 35.2 | 28.8 | 23.1 | 3400 | 3 x 10$^{6}$ |
| | Gute Sedo | | 1.0 | 14.4 | 30.5 | 35.5 | 19.6 | 3987 | |
| Wuchale | Totito | Outcrop | 0.5 | 10.4 | 18.0 | 45.4 | 35.2 | 3700 | 3.3 x 10$^{6}$ |

# CHAPTER THREE

# 3. MATERIALS AND METHODOLOGY

## 3.1 Materials and Reagents

### 3.1.1 Apparatus and Instruments

Instruments and apparatus used for this study were; Jaw crusher, Cross-bitter mill, Sieve Shaker and Sieves, Crucibles, Electronic Weighing Balance, Gas Compressor and flotation cell at AAiT (Mechanical operation lab).

### 3.1.2 Sample Collection

The 10 kg of coal from surface and excavated samples were collected from the Konta zone Ela-Hanchano Woreda coal mining area of Southwestern Ethiopia region. The samples were reduced sizes by crushed and ground in the laboratory to 80% passing through 0.5mm sieve to obtain different particle sizes fraction for flotation tests (Fuerstenau & Han, 2009). The purpose of collecting and preparing a sample of coal is to provide at test sample which analyzed would provide test results representative of the a lot sampled. This makes it easier to guarantee that the coal from which the sample is drawn is accurately described. Accurate analysis depends on careful sample preparation and sampling.

Figure 6: Coal sample’s collected site

### 3.1.3 Sample Handling

The samples would be stored in plastic bags to contamination, ensure proper storage and transported to the laboratory analysis.

### 3.1.4 Sample Preparation

Coal samples were collected from mining area of the Ela-Hanchano coal deposit and the sample was crushed, and ground to 0.5mm size, and screened into three narrow size fractions: -500µm+250µm, -250µm+125µm, and -75µm (Patnaik et al., 2020). From the pulverized each size fraction was weighed with electronic mass balance in the AAiT mechanical laboratory and analyzed for proximate analysis, then stored in plastic bags until required for flotation tests, as shown (Fig 6).

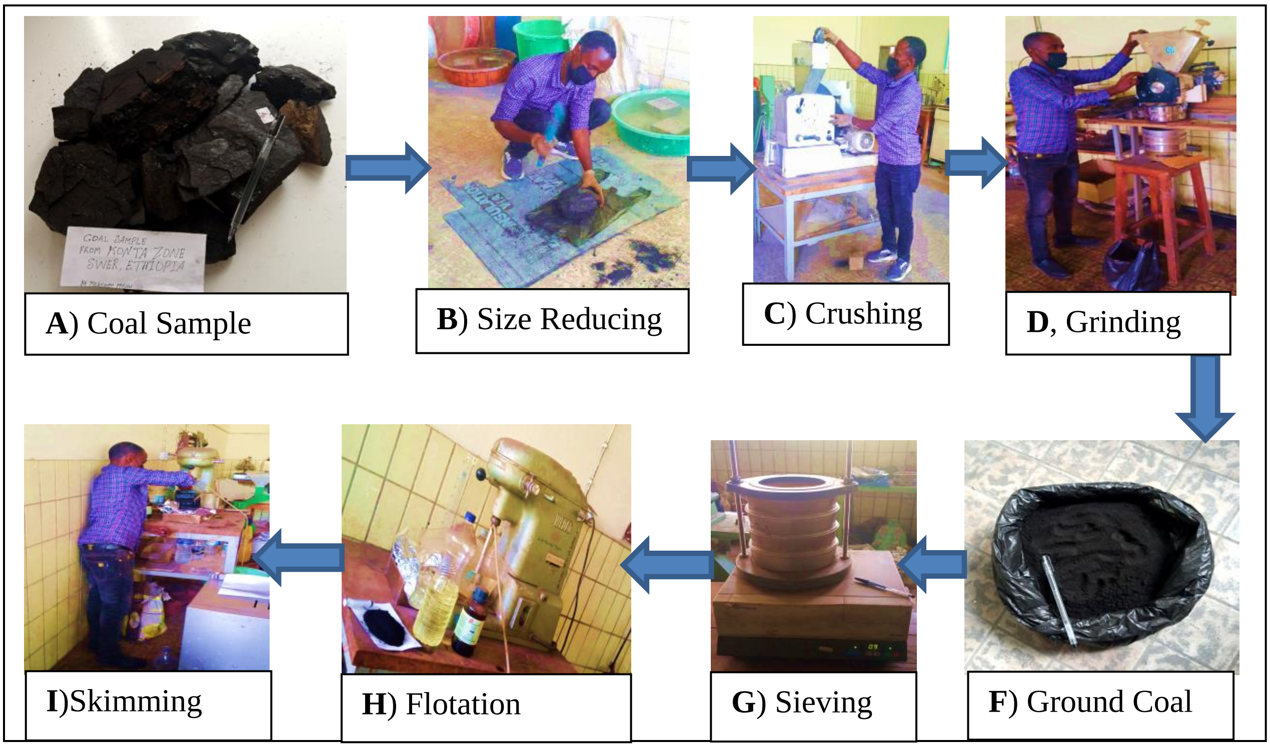


Figure 7: The experimental coal flotation flow diagram

### 3.1.5 Flotation Tests

Flotation experiments were carried out using a laboratory-scale flotation cell. The experimental setup would include a series of batch flotation tests to determine the impact of the following variables:

- Reagents: Flotation reagents used in this study used N-Octanol as a foaming frother and kerosene as a collector in accordance with those uses in the flotation experiment.
- Particle Size Distribution: The sample would be crushed, ground, and screen into three narrow size fractions: -500 µm+250µm, -250µm+125µm & -75µm would be evaluated for different particle size fractions.

- Fixed Conditions of Pulp Density, Flotation Time and Air Flow Rate.

#### 3.1.5.1 Flotation Procedures

The following steps were followed to perform froth flotation experiments using fine particle sized coal samples:

1. **Preparation of the Coal Sample and Flotation Setup:**

Fine coal particles were prepared previously and a wedge flotation cell with a 3L capacity was used. Initially, 2L of tap water was poured into the flotation tank, followed by the addition of 100g of the coal sample. The mixture was agitated for 3 minutes at a stirring speed of 1,500 rpm (Kasomo et al., 2019) to ensure complete wetting of the particles, with the air valve kept closed.

2. **Addition of Collector and Frother:**

A specified dosage of kerosene (acting as the collector) was introduced, and the mixture was agitated for an additional 2 minutes, keeping the air valve closed. Subsequently, the required amount of n-octanol (frother) was added, and the air valve was opened to allow air into the flotation cell, facilitating bubble-particle interactions.

3. **Bubble Formation and Particle Collection:**

Once bubble formation commenced, 0.5L of water was added to fill the flotation cell. The overflowing bubbles, carrying the particles, were collected as froth. This process continued until white foam appeared, indicating the attachment of entirely solid particles to the collector.

4. **Drying and Yield Calculation:**

The collected particles were filtered and dried in a hot oven at 80°C. The concentrate yield was calculated using the following formula:

$$\textbf{Yield}\ (\%) = \frac{\textbf{Mass of Concentration in grams}}{\textbf{Mass of Feed in grams}}\boldsymbol{X100}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

### 3.6 Analysis Techniques

#### 3.6.1 Proximate Analysis

The American Society for Testing and Materials (ASTM 3286) were used to determine the coal samples' moisture, ash, volatile matter, and calorific value, respectively (Riasetiawan et al.,2023). Proximate analysis of the D3173, D3174, and D3175 coal samples involves heating crushed coal to specified temperatures under controlled conditions and determining proportional changes in mass produced in the process. It is used to determine the relative proportions of volatile and nonvolatile organic material produced from the coal by heating in the absence of air, referred to as volatile matter and fixed carbon, respectively, as well as the proportion of moisture present and the proportion of noncombustible residue, or ash, left behind after the organic material is burned. It gives important and critical information regarding the appropriateness of coal for a specific industrial or domestic application. The American Society for Testing and Materials' (ASTM) coal analysis standards serve as the foundation for this analysis method, which yields data on the coal's moisture content, volatile matter, ash content, and fixed carbon.

### 3.6.1.1 Determination of Moisture Content

The moisture content in coal greatly affects its calorific value and combustion efficiency. High moisture content reduces heating efficiency as extra energy is required for water evaporation during combustion. The moisture level was established by drying 1g of coal sample at a temperature 105$^{o}$C for one hour in the oven a stable weight reached. After heating, the crucible was transferred to a desiccator to cool down for a few minutes. Calculation of Moisture Content: The formula used for calculating moisture content is as follows:

$$\textbf{Moisture Content}\ (\%) = \frac{\textbf{Weight loss during drying (g)}}{\textbf{Initial weight of sample (g)}} \boldsymbol{X100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

### 3.6.1.2 Determination of Volatile Matter

The volatile matter content was determined using the ASTM D-3175 testing procedure, which involves weighing 1g of an air-dried sample in a crucible with a lid to prevent oxidation, was heated at 950°C for seven minutes in the muffle furnace. After heating the sample is transferred to the dissector to cool down for a few minutes and finally, the volatile matter is determined by taking the ratio of the residue to the sample taken and expressed by percentage forms. The standard method for analyzing volatile matter involves heating a sample of coal under specific condition. Volatile matter is the thermal decomposition of liberated products when coal is heated at a higher temperature within the absence of air.

Calculation of Volatile Matter: The percentage of volatile matter is calculated
using the formula:

$$\textbf{Volatile Matter}\ (\%) = \frac{\textbf{Weight Loss (g)}}{\textbf{Initial Weight of Sample (g)}} \boldsymbol{X100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

### 3.6.1.3 Determination of Ash Content

Ash content analysis is also proximate analysis part of coal testing method in the laboratory, providing to understandings the non-combustible mineral matter present in the coal. Ash content determination is a process that measures the inorganic residue left after burning a sample to remove organic matter. The ASTM D-3174 standard procedure was used for this analysis. A 1 g sample of finely ground coal was placed in a ceramic crucible and heated in a muffle furnace at 750°C for two hours until all organic matter was burned off. After complete combustion the sample is allowed to cool and the residue which is the ash is weighed.

Calculation of Ash Content: The percentage of ash content is calculated using the following formula:

$$\boldsymbol{Ash\ Content}(\%) = \frac{\textbf{Weight of Ash Residue (g)}}{\textbf{Initial Weight of Sample (g)}}\ \boldsymbol{X}\ \mathbf{100} \ldots\ldots\ldots\ldots\ldots\ldots.(\mathbf{4})$$

### 3.5.1.4 Determination of Fixed Carbon

Fixed carbon (FC) analysis is a fundamental aspect of coal testing, which helps to determine the solid combustible residue left after volatile matter and moisture have been driven off during combustion. The percentage of fixed carbon in coal determines its quality; it should be as high as feasible. The relationship between fixed carbon and volatile matter is inverse ; due to the nature of the carbonization process and the characteristics of these components: As coal matures (increases in rank from lignite to anthracite), the fixed carbon content increases while volatile matter decreases. Fixed carbon analysis, the method used was an indirect determination based on proximate analysis results. Fixed carbon is the portion of coal that remains after moisture, ash, and volatile materials are removed, and it plays a crucial role in determining the energy content and burning characteristics of coal. The fixed carbon content was not measured directly but rather calculated using the following formula.

Fixed Carbon (%) = 100 − (Moisture (%) + Ash (%) + Volatile Matter (%))

### 3.6.2. Determination of Sulfur Content

The sulfur content of the coal samples was determined using chemical analysis methods at the Ethiopian Geological Institute laboratory. The sulfur presents in the coal appears in various forms, including organic and inorganic (pyritic) sulfur. The sulfur content was evaluated by converting it into sulfur dioxide ($SO_2$) during combustion. During the sulfur analysis, a chemical precipitation method was used, following ASTM standard procedures. The sulfur content in the coal sample was determined by converting sulfur into sulfur dioxide ($SO_2$) during combustion, followed by precipitation as barium sulfate ($BaSO_4$). The $SO_2$ was then dissolved in water to form sulfuric acid, which was subsequently precipitated as barium sulfate ($BaSO_4$) using barium nitrate ($Ba(NO_3)_2$). The reaction is represented as follows:

$$\textbf{Sulfur}\ \% = \frac{\textbf{32 x Weight\_of\_BaSO4\_formed (g)}}{\textbf{233 x Weight\_of\_sample\_taken (g)}}\ \boldsymbol{X}\ \mathbf{100} \ \ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$2H_2SO_3 + O_2 \rightarrow 2H_2SO_4$$

$$H_2SO_4 + Ba(NO_3)_2 \rightarrow BaSO_4\downarrow + 2HNO_3$$

### 3.6.3 Determination of Calorific Value

The calorific value of coal, it indicated by energy contents was measured using an Adiabatic Bomb Calorimeter at the center of Ethiopian Geological Institute laboratory. A 1g powdered coal sample was placed into crucible and burned in a high-pressure oxygen atmosphere. The observed increase in temperature within a specified volume of water was recorded, and the gross calorific value (GCV) was determined using the formula:

$$GCV = \frac{(\mathrm{tW} - \mathrm{e1} - \mathrm{e2} - \mathrm{e3})}{\mathrm{m}}$$

Where:

GCV = Gross calorific value in Btu/lb. ,

t = Temperature

W = Energy equivalent of calorimeter in Cal/$^{o}$C,

e1 = Correction in calories for the heat of formation of nitric acid ($HNO_3$) = (ml of standard alkali solution used in acid titration) if 0.0709N alkali was used for the acid titration,

e2 = Correction in calories for the heat of formation of sulfuric acid ($H_2SO_4$),

e3 = Correction in calories for the heat of combustion of fuse wire and

m = mass of coal sample taken in gram

# CHAPTER FOUR

# 4. RESULTS AND DISCUSSIONS

## 4.1 Flotation Results

The flotation performance was evaluated by determining the ash, calorific value, sulfur, volatile matter, fixed carbon, and combustible recovery values on the obtained products at the end of the experiment (Önen & Karaoğlan, 2023).The flotation tests carried out on coal samples of different particle sizes, collector, and frothier dosages show very distinct trends in flotation performance, which was mainly evaluated by the recovery percentages. The flotation behavior of coal particles was observed following the addition of a collector (kerosene) during an initial conditioning time of 3 minutes. At this stage, large bubbles formed, but the particles did not attach to the surface of the oily bubbles. However, upon introducing n-octanol as a frother and extending the conditioning time to 2 minutes, the bubbles became stabilized and reduced in size, enhancing the flotation process. The formed foam particles were skimmed off and filtered by using aluminum foils paper to separate the residue from its solution for 10 minutes shown (Fig.7). The filtrate of concentrate (foam) was dried and taken for proximate analysis. The flotation tests carried out on coal samples of different particle sizes, collector, and frothier dosages show very distinct trends in flotation performance, which was mainly evaluated by the recovery percentages. The coal flotation of the study area, such as collector and frothier dosages, yield, ash content, recovery, grade, and efficiency analysis results, are shown in Table 5.

Figure 8: Concentrated coals after flotation in the aluminum foil paper of the study area

Table 5: The experimental results of flotation of the study area

| Particle Sizes (µm) | Collector Dosages(ml) | Frothier Dosages(ml) | Yield (%) | Ash Contents (%) | Recovery (%) | Grades (%) | Efficiency (%) |
|---|---|---|---|---|---|---|---|
| **(-500 + 250)µm** | 5 | 2 | 59.69 | 10.01 | 62.70 | 89.99 | 56.42 |
| | 10 | | 50.30 | 10.53 | 52.51 | 89.47 | 46.98 |
| | 5 | 4 | 68.35 | 11.03 | 70.96 | 88.97 | 63.13 |
| | 10 | | 70.21 | 11.16 | 72.78 | 88.84 | 64.66 |
| **(-250 + 125)µm** | 5 | 2 | 64.42 | 9.65 | 66.20 | 90.35 | 59.81 |
| | 10 | | 61.90 | 8.74 | 64.24 | 91.26 | 58.63 |
| | 5 | 4 | 66.43 | 8.84 | 68.86 | 91.16 | 62.77 |
| | 10 | | 73.50 | 10.36 | 74.92 | 89.64 | 67.16 |
| **(-75)µm** | 5 | 2 | 72.53 | 10.15 | 75.03 | 89.85 | 67.41 |
| | 10 | | 74.33 | 11.31 | 75.90 | 88.69 | 67.32 |
| | 5 | 4 | 86.60 | 12.16 | 87.58 | 87.84 | 76.93 |
| | 10 | | 76.07 | 11.60 | 77.42 | 88.40 | 68.44 |

### 4.1.1 The Effects of Particle Sizes and Recovery .

Particle size has a major impact on flotation rate making it one of the most crucial factors in coal flotation (Sokolovic&Miskovic,2018). Flotation efficiency was strongly impacted by particle size (Table 5, Figure 8-10). Coarser fractions (-500+250 µm) had lower recoveries (52.51–72.78%), whereas finer particles (-75 µm) had the highest recovery (87.58%). This is consistent with the idea that bubble-particle adhesion is enhanced by finer particles (<125 µm) because they have more surface area and better hydrophobicity. Stable transit to the froth layer is made possible by smaller particles' decreased detachment forces. However, mechanical entrainment of fine gangue resulted in a greater ash concentration (12.16%) in the -75 µm fraction (Figure 11), highlighting the necessity of tailored reagent regimens to reduce ash carryover. The following particle sizes and their effects on the recovery:

- -500+250µm: The percentages of coal recovery ranged from 52.51% to 72.78% using the higher doses of frothier (4ml), which gave better recovery than 2ml of frothier.

- -250+125µm: The recovery percentages show the range of 64.24% to 74.92%, when reducing the particle size fractions and the dosage of frothier which clear evidence of increased coal recovery.

- 75µm: The recovery percentages of the finest size fraction also gave the highest recoveries, with recovery values touching 87.58%. These results suggest improved liberation and surface area available for particle-bubble interaction in finer particles. Hence, the coarser particles (-500+250 µm) show lower recoveries overall compared to finer particles (-75µm), as shown (Fig. 8).

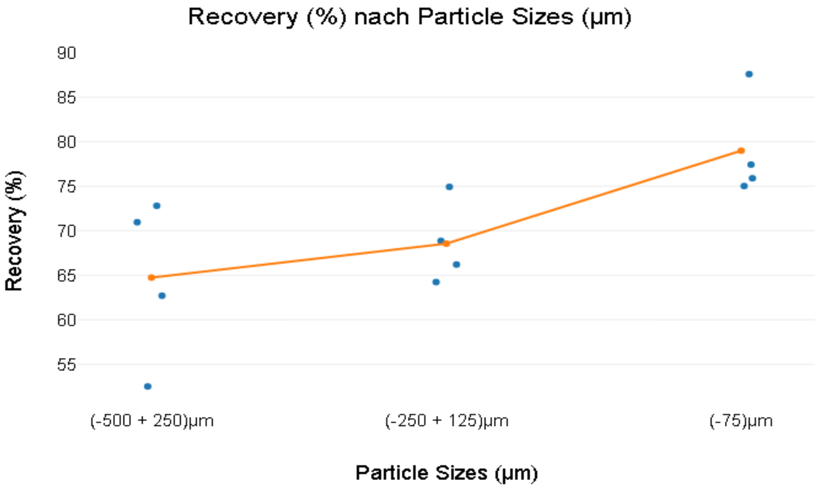


Figure 9: Particle Sizes (µm) verses recovery (%) of the study area.

In view of that, the mean recovery values are consistent with the findings of Figure 10, which show an inverse relationship between particle size and recovery.  It is estimated that the 75 µm fraction recovered 78.98% of the samples, compared to 68.56% for the 250+125 µm fragment and 64.74% for the 500+250 µm fragment. As a result, it is evident a higher coal capture rate may be achieved during flotation if liberation and surface chemistry are optimized in finer particles.

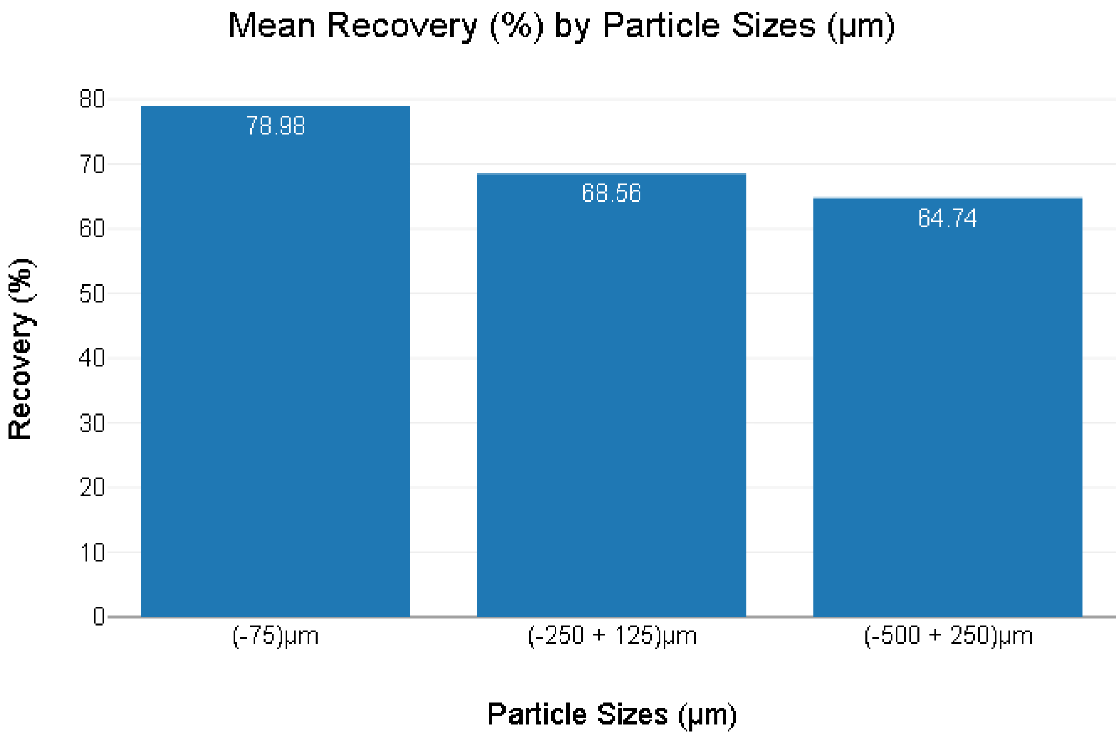


Figure **10**: Mean recovery verses particle sizes (µm) of the study area

This graph shows in Figure 11 mean yield and mean recovery patterns over particle sizes. The difference between mean yield and mean recovery increases from coarser to finer fractions, even though both metrics get better as particle size decreases. Effective separation is indicated by the near alignment of mean yield (77.38%) and mean recovery (78.98%) for particles with a size of −75 µm. Conversely, coarser fractions (−500+250 µm) show a wider gap (mean yield: 62.14%, mean recovery: 64.74%), indicating mechanical inefficiencies like partial bubble coverage or particle detachment.

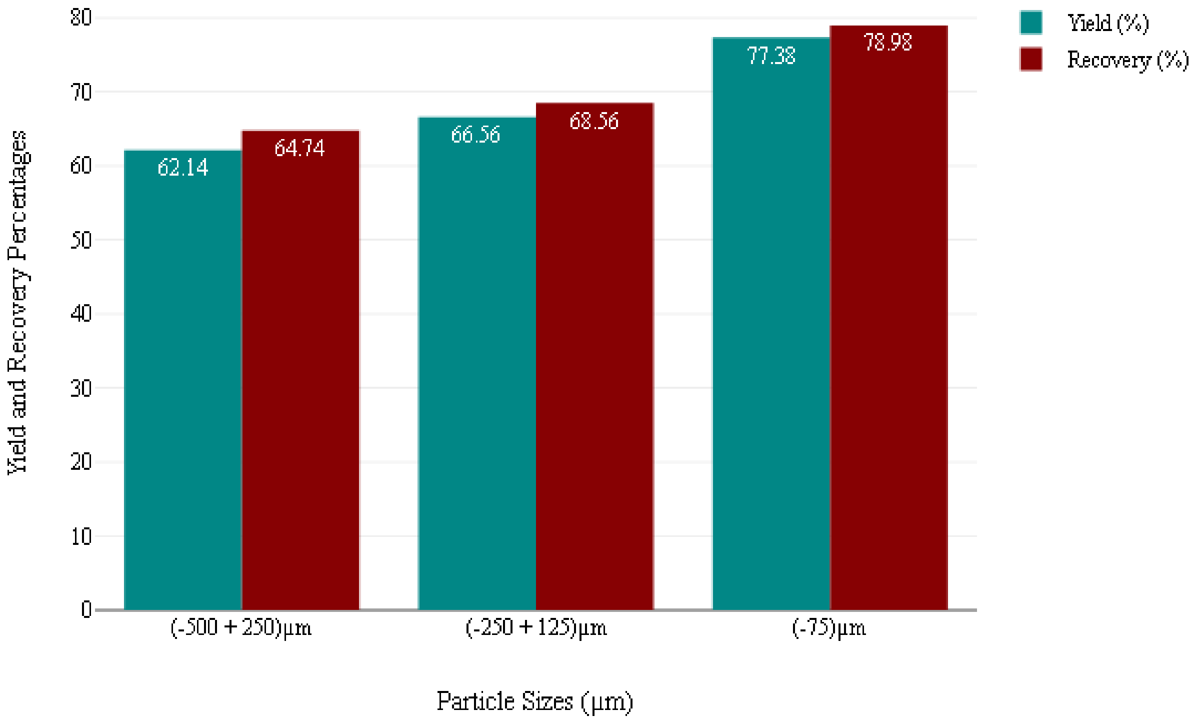


Figure 11: Particle sizes verses mean yield (%) and mean recovery (%) of the study area

The relationship between particle size and ash content, as given picture of in Figure 12, make known a direct correlation between decreasing particle size and increasing ash content with particle size hit the highest point at 12.16% in 75 µm particles. This is caused by mechanical entrainment of fine gangue minerals (gangue materials) in the froth layer, a common fine particle flotation issue. Coarser fractions (-500+250µm) contain less ash (10.01% – 11.16%), since larger particles are prone to entrainment. The figure indicates a trade-off: finer particles achieve maximum recovery but lower concentrate purity; hence ash carryover must be minimized by using optimum reagent regimes.

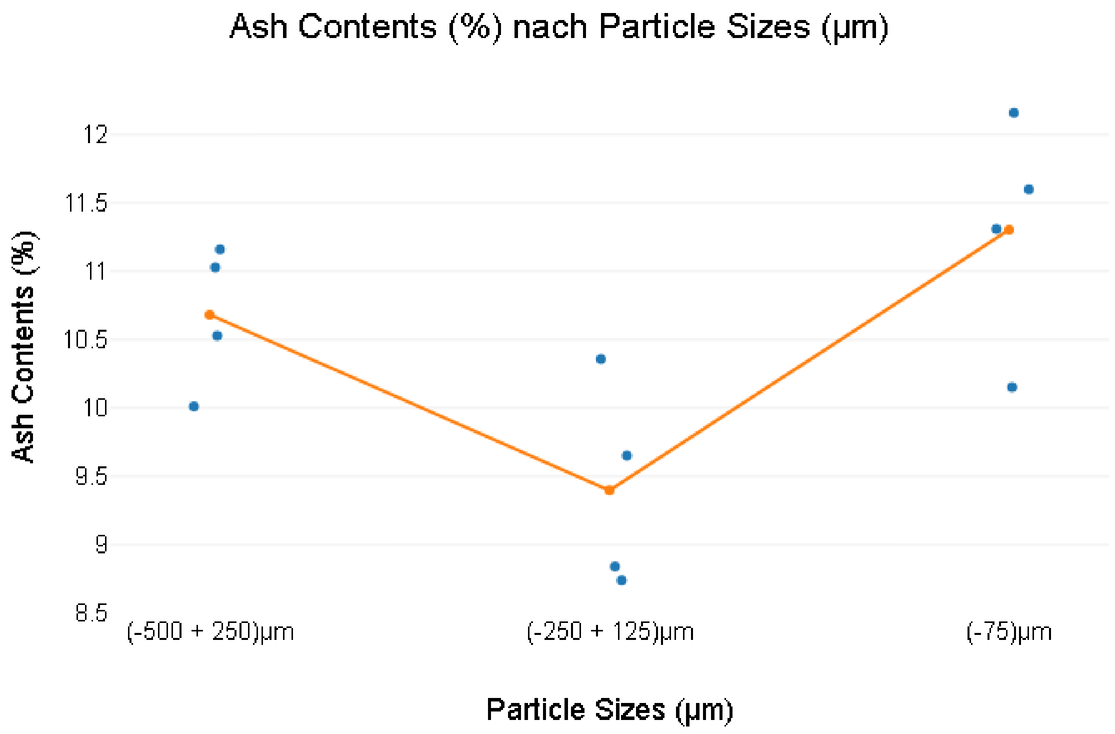


Figure 12: Particle sizes (µm) verses ash contents (%)

Grade (combustible content) decreases slightly with finer particles showing a relationship with ash content in Figure 13. The particle size fraction of -75 µm has a grade of 87.84%, which is slightly lower than coarser fractions (88.69% - 91.26%). This is a reflection of the two-way effect of particle size: finer particles achieve improved recovery, but bring together impurities and coarser particles achieve better purity at the expense of reduced recovery.

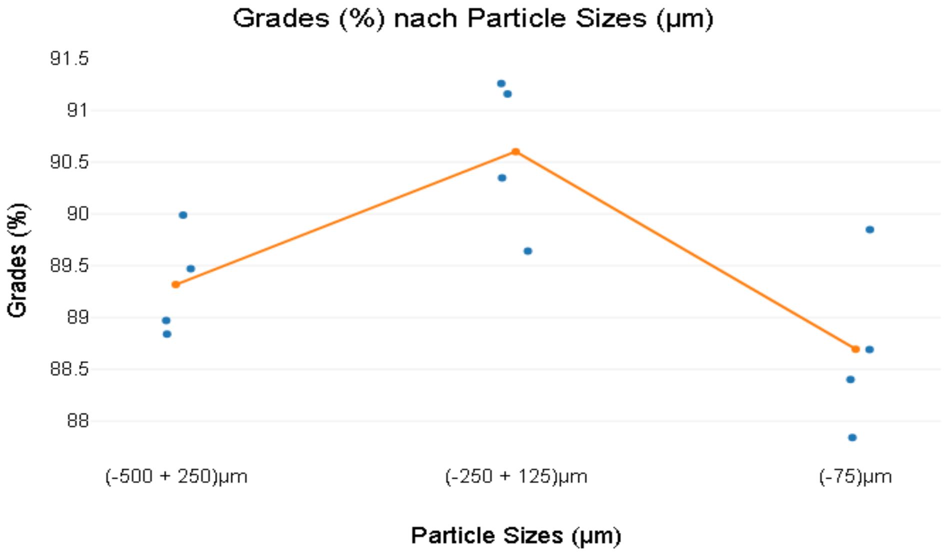


Figure 13: Particle sizes (µm) verses grade (%)

### 4.1.2. The Effects of Collector Dosages on Coal Flotation's

The size of bubbles has a considerable impact on the effectiveness of flotation, particularly when it comes to very fine coal particles. To facilitate the flotation of fine materials, a larger surface area is necessary, which means that it is essential to generate small bubbles (Önen & Karaoğlan, 2023). The collector dosage played a crucial role in improving recovery at 5 ml collector dosage, recoveries were consistently good but slightly lower than the recoveries achieved at 10 ml dosage within the same particle size fraction. At 10 ml collector dosage flotation recovery improved particularly in finer particle sizes suggesting that higher collector dosage increases hydrophobicity promoting better bubble-particle attachment. Lower dosages for all particle size ranges at (5 ml) generally result in moderate recoveries.

Collector dose had a direct effect on recovery and concentrate quality. The recovery decline for coarser particles (-500+250 µm) at 10 ml kerosene (62.70% to 52.51% with 2 ml frother) was probably caused by either slime coating or bubble overload from over-hydrophobicity (Fig 13). Conversely, smaller particles (-75 µm) could tolerate higher collector dosages and recovered 77.42% at 10 ml. A 5 ml collector and a 4 ml frother produced the highest recovery (87.58%) for -75µm particles, suggesting a trade-off between froth stability and hydrophobicity (Table 5). Through contaminant entrainment or froth instability, an overabundance of collectors may lower grade (Fig 15). The rate of coal concentration is higher up to 5minutes were good and after that the rate decreased gradually for the remaining time concentrations for the coarser and medium sizes.

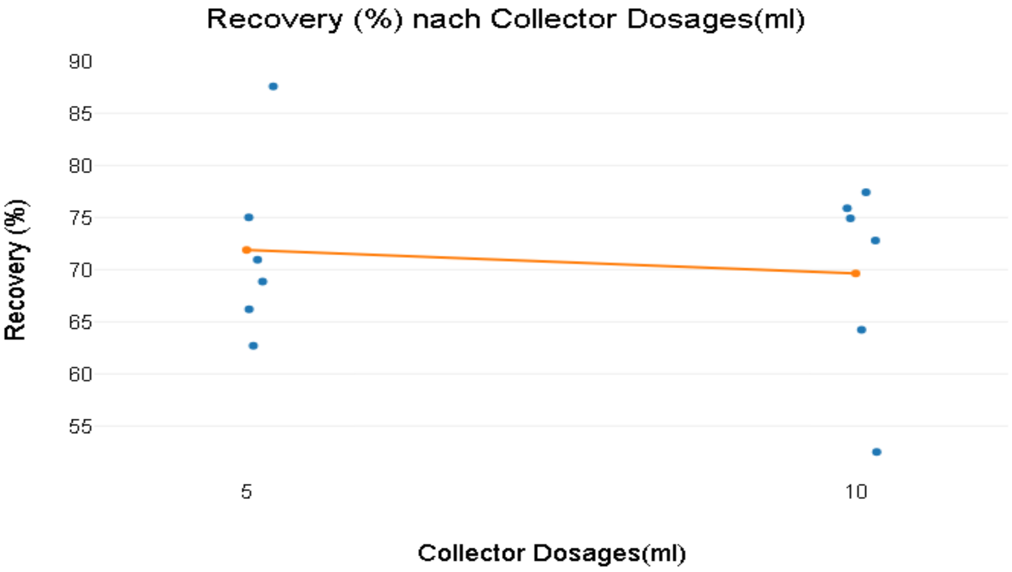


Figure 14: Collector dosages (ml) verses recovery (%) of the study area

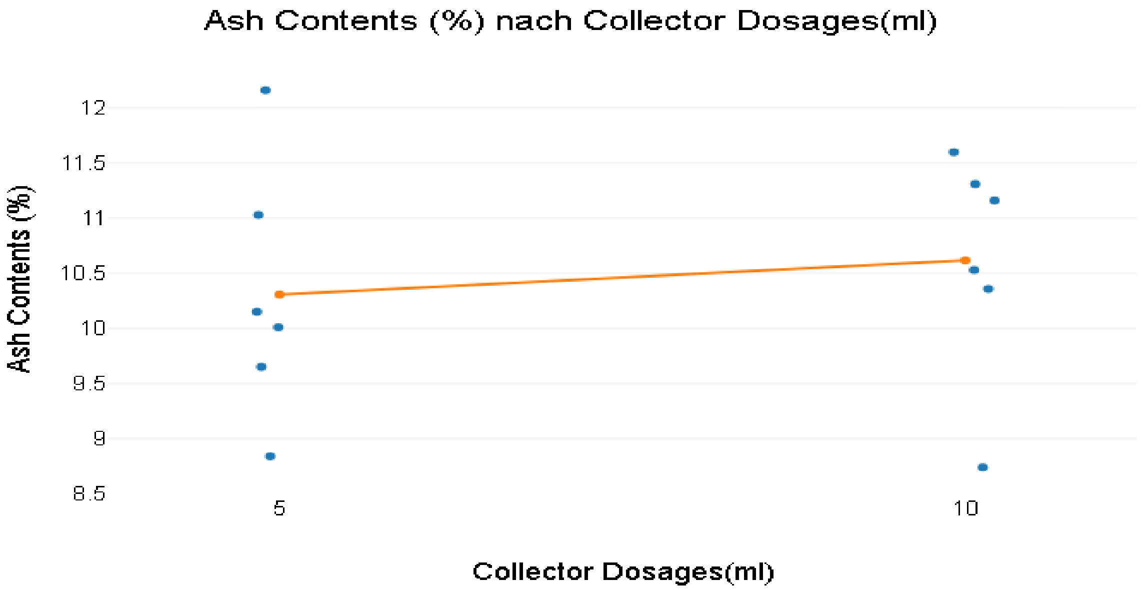


Figure 15: Collector dosages (ml) verses ash Contents (%) of the study area

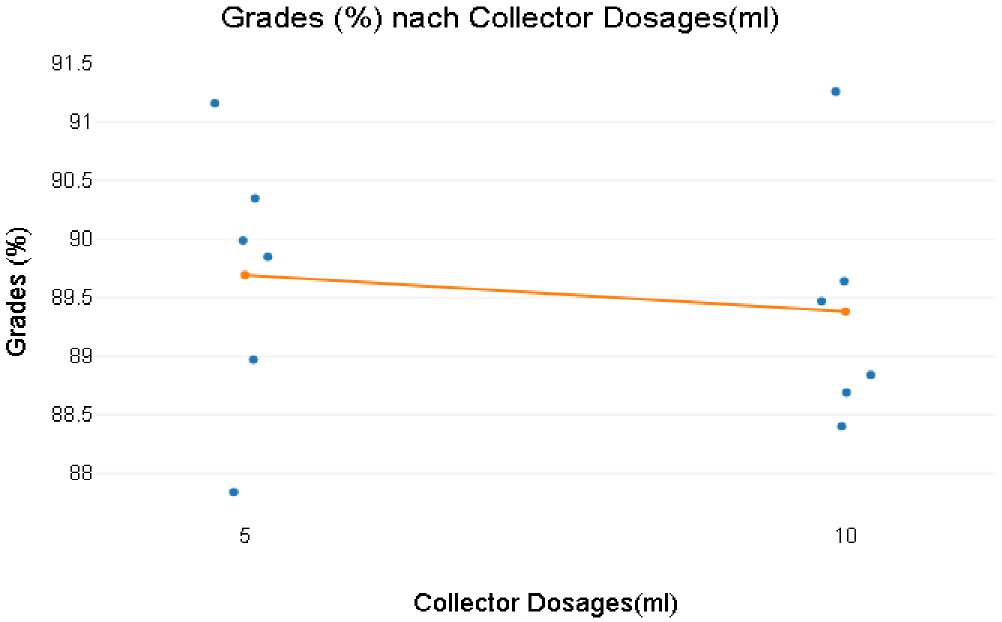


Figure 16: Collector dosages (ml) verses grades (%) of the study area

### 4.1.3 The Effects of Frothier Dosages on Coal Flotation's

The frothier dosage significantly affected the flotation performance for all particle sizes a dosage of 4ml gave better recovery than 2ml, probably because of improved froth stability and reduction in bubble size which enhanced the capture of particles. The recovery at 2ml frother dosage is lower than higher dosages especially at fine particles. This indicates that lower frother levels provide insufficient frothing ability for stable bubble production. For the

-250+125 µm particles with the 5 ml collector, 66.2% recovery was achieved using 2 ml frother, which increased the recovery rate to 68.86% with the 4 ml frother. 4 ml frother dosages consistently improve recovery across for all of the particle sizes especially with the smaller particles; recovery can hit up to 87.58%. For -75µm particles with 5 ml collector the recovery percentage improves from 75.03% at (2 ml frother) to 87.58% at (4 ml frother). Overall frother dose greatly stabilized the bubbles and improved recovery. When n-octanol was raised from 2ml to 4ml, recovery improved for all sizes, but it was most pronounced for -75µm particles (75.03% to 87.58%) (Figure 16).The 4ml dosage reduced bubble coalescence and produced smaller, more stable bubbles with a larger surface area for particle capture. However, an excessive amount of frother (4ml) somewhat increased the amount of ash (11.60% vs. 10.15% at 5ml for -75µm) due to entrained hydrophilic gangue (Figure 17).

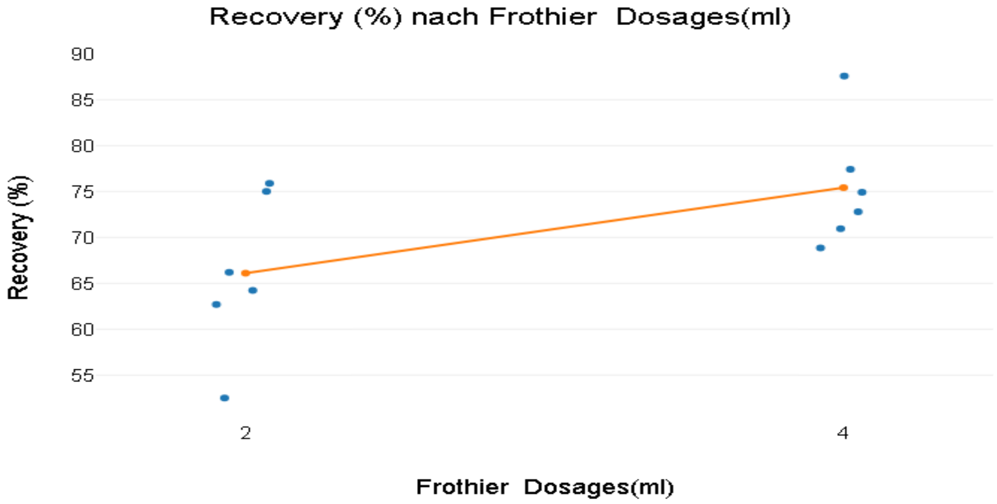


Figure 17: Frother dosages (ml) verses recovery (%) of the study area

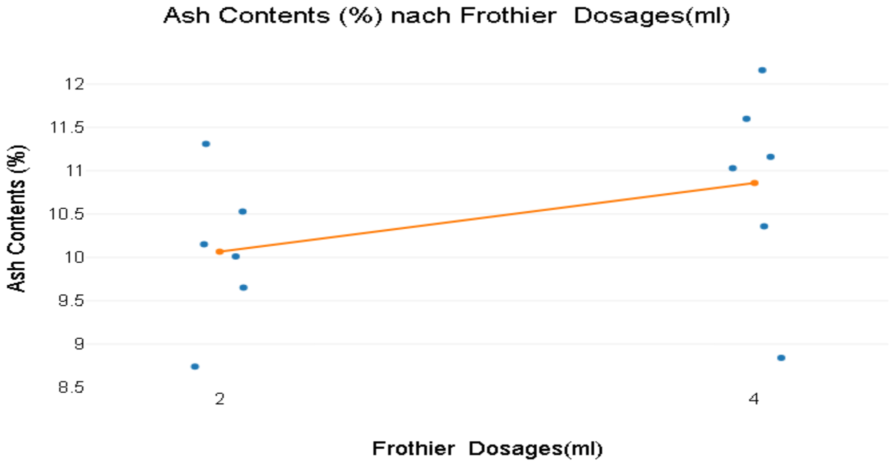


Figure 18: Frother dosages verses ash contents (%) of the study area

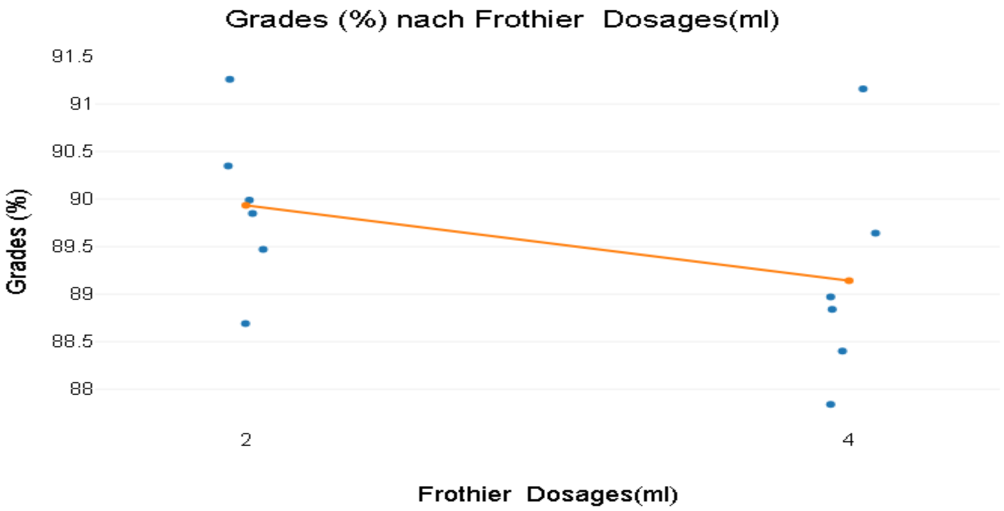


Figure 19: Frother dosages (ml) verses grades (%) of the study area

### 4.1.4 Optimal Flotation Parameters

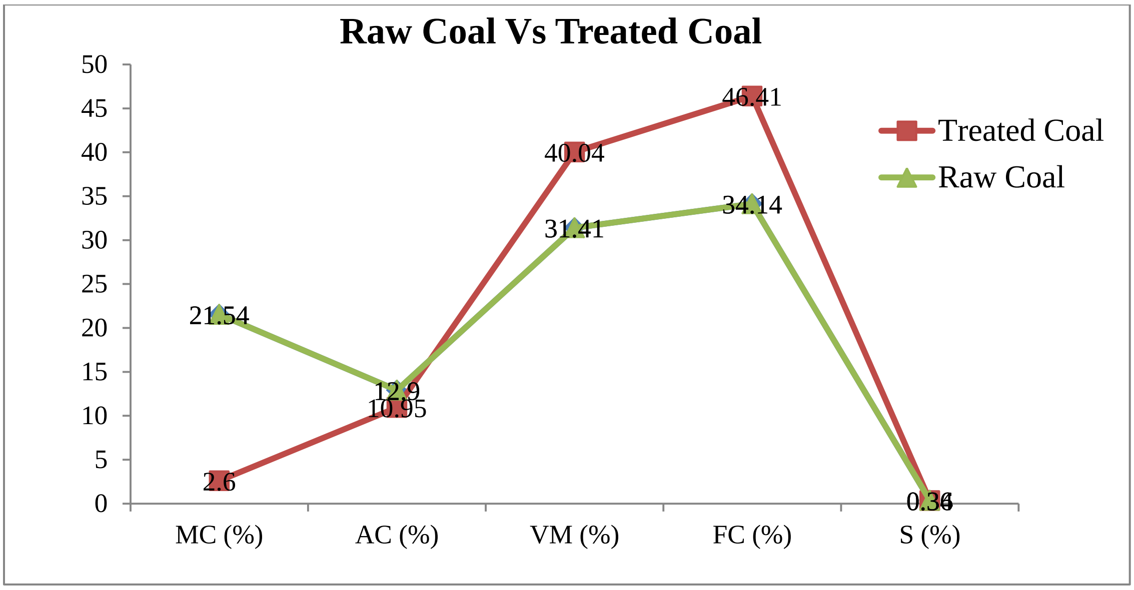
The highest efficiency (76.93%) occurred at -75 µm with 5 ml kerosene and 4 ml n-octanol (Table 5). This combination balanced particle-bubble attachment (via collector) and froth stability (via frother), maximizing recovery while maintaining grade (~88%). Coarser particles required lower collector doses to avoid overloading, while finer fractions benefited from higher frother levels to stabilize smaller bubbles.

## 4.2 Proximate Analysis Results

The gross impurities in the coal samples were identified using proximate analysis method, which also helped determine whether the samples were suitable for industrial or residential uses. According to (Speight, 2005), proximate analysis method is determined based on the American Society for Testing and Materials' (ASTM) standards. The proximate analysis data includes moisture content, volatile matter, ash content, and fixed carbon. In order to classify coal and assess whether it is suitable for a given industrial use, proximate analysis is essential. The moisture content, volatile matter, ash content, and fixed carbon, results of the study are shown (Table 6; Fig. 19) respectively.

Table 6: The proximate analysis, calorific value and sulfur value of raw and treated Coal samples

| **Raw Coal** | | | | | |
|---|---|---|---|---|---|
| MC (%) | AC (%) | VM (%) | FC (%) | CV (cal/gm) | S (%) |
| 21.54 | 12.90 | 31.41 | 34.14 | 4804.07(8647.33Btu/1b.) | 0.36 |
| **Treated Coal** | | | | | |
| MC (%) | AC (%) | VM (%) | FC (%) | CV (cal/gm) | S (%) |
| 2.60 | 10.95 | 40.04 | 46.41 | 6418.15(11552.67Btu/1b.) | 0.34 |



Abbreviations: MC = Moisture Content, VM = Volatile Matter, FC = Fixed Carbon, CV = Calorific- value and S = Sulfur.

Figure 20: The proximate analysis and sulfur data of raw and treated coal samples from the study area.

### 4.2.1 Moisture Content

The obtained results of moisture content for raw coals was 21.54% and the moisture content of treated (floated coal) was 2.60% as shown in the Table-6 and Fig-20. Coals can have moisture contents ranging from roughly 5% to nearly 70% (Wakuma & Assaba, 2017). The results revealed that the moisture content in treated coal was lower than in raw coal. This result suggests that treated coal has a higher caloric value and better burning characteristics than raw coal. The moisture level in coal is influenced by its maturity level (Ryemshak & Jauro, 2013). Since the moisture content of black coals is extremely low and does not interfere with their use, water in high-rank coal is less significant (Bratek et al., 2002). Water, on the other hand, has a major impact on the combustion, gasification, and liquefaction processes of low rank coals. Reduced efficiency, higher transportation costs, and increased carbon emissions are the outcomes of the high moisture content (Yu et al., 2013). Moisture content analysis of coal is vital for determining its quality, efficiency, and suitability for various industrial processes. By understanding and managing moisture content, industries can optimize coal handling, transportation, and combustion processes, ensuring higher energy efficiency and reduced environmental impact. Moisture reduces the heating value (calorific value) of coal, as energy is used in evaporating the water during combustion. High moisture content results in lower efficiency in power generation as more energy is needed to dry the coal during combustion. weight is achieved (D05 Committee,2021). The difference between the initial weight and the dried weight gives the total moisture content (Speight, 2005, 2015).

### 4.2.2 Ash Content

Ash is an impurity substance that will not be burned (Usman et al.,2021). On the Ethiopian Geological Institute of Laboratory Analysis the ash content that was obtained in the results for raw coal was 12.90% and treated coal was 10.95%, as shown in the Table 6, implies the ash content of raw coal is higher than that the floated (treated) coal. The ash content increases as the particle size decreases when the particle is smaller than 125µm (Cheng et al., 2019). When the particle size is lower than 125µm, the ash concentration rises in proportion to the particle size distribution or surface area. Specifically, the size fraction of −75µm has an ash percentage of up to 12.16%, which is clearly larger than the ash content of other fractions, shown in Table 5 Laboratory experiment results of the study area. Consequently, the primary source of ash is high-ash fine mud, which readily breaks down the concentrates by mechanical entrainment during the flotation process. To increase coals recovery and lower the amount of ash in clean coal, a collector type with high separation efficiency must be chosen (Cheng et al., 2019). Ash significantly affects both the diffusion of oxygen to the fuel surface during char burning and the transfer of heat to the fuel surface. The study's volatile matter and ash content readings are both satisfactory and acceptable (Wakuma & Assaba, 2017). It's used to evaluate the nutritional value of a food sample and to prepare it for elemental analysis (Wiyantoko et al., 2018). Ash residue is calcined to constant mass after an air fuel sample is burned (ashing), which is a well-accepted technique for determining the elements of coal minerals (ash content).

### 4.2.3 Volatile Matter

Volatile matter refers to those combustible constituents of coal that vaporize when coal is heated (Wiyantoko et al.,2018). The experimental result obtained from volatile matter for raw and treated coal samples that were ranged 31.41% and 40.04% respectively as shown in Table-6. The higher volatile matter content in coal indicates that the coal's lower rank and rising volatile matter also resulted in higher amounts of flammable gasses, which in turn reduced the amount of fixed carbon and, ultimately, the coal's heating value (Usman et al., 2021). Coal's volatile matter content varies according to its rank. Volatile matter is one of the most crucial factors that determines the appropriate use of a coal and is known to decrease with increasing rank (Ryemshak & Jauro, 2013). Volatile matter (VM) in coal refers to the components of coal, with the exception of moisture, which are released at high temperature in the absence of air, which is generally a mixture of short and long chain hydrocarbons, aromatic hydrocarbons and some sulfur. The higher VM content is more characteristic of low-rank coals, while the decreased value is more typical of higher-rank coals. Volatile matter is the thermal decomposition of liberated products when coal is heated at a higher temperature within the absence of air. The volatile matter obtained during the pyrolysis of coal contains more combustible gases like carbon monoxide, hydrogen, hydrocarbons, ammonia, tar and incombustible gases like carbon dioxide and steam. The value of the volatile matter is used to establish coal ranks, to give the basic information of coal importing and exporting and to tell the burning characteristics of coal like reactivity and flame stability.

### 4.2.4 Fixed Carbon

The fixed carbon content of coal is the carbon found in the material remaining after the expulsion of volatile materials. The study also shows that treated coal has more fixed carbon than raw coal. Because fixed carbon, the solid residue left over after devolatilization, is important because it may be used to calculate how much coke can be produced from coal carbonization (Ryemshak & Jauro,2013). The amount of fixed carbon content for raw and treated coal that was obtained from the experimental result of the geological survey of Ethiopia laboratory was found in the ranges of 34.14% to 46.41% respectively as described in Table 6. The raw coal samples were showing less than 40% of the fixed carbon content which implies that lowering the carbon number highly affected the heating efficiency of the coal, but the treated coal sample was greater than 40% of fixed carbon content which implies that higher the carbon number and highly heating efficiency of the coal. Fixed carbon determines the rank and quality of a coal sample (Ryemshak & Jauro, 2013). High carbon content is essential for coke making coal because it is the mass that forms the actual coke on carbonization (Jovanovski et al.,2023). Fixed carbon content is used as an estimate of the amount of coke that will be obtained on carbonization. The calorific value increases as the percentage of fixed carbon increases (Wakuma & Assaba, 2017).

## 4.3 Ultimate Analysis

### 4.3.1 Sulfur Content

In general, Ela-Hanchano coal contains low sulfur content, but sulfur concentration shows a little decrease after the flotation process. Sulfur content marginally decreased from 0.36% (raw) to 0.34% (treated), indicating limited efficacy of flotation in sulfur removal (Table 6). Although the sulfur content in the treated coal is relatively low and within acceptable limits for many industrial applications. However, the sulfur content of the raw coal sample is slightly dropped in the treated coal sample. This slight decrease implies that the froth flotation technique employed in this investigation has little effect on the removal of sulfur. Sulfur in coal exists in different forms, such as organic sulfur and inorganic sulfur (sulfides like pyrite). Froth flotation is primarily effective for reducing inorganic impurities like ash but is less effective for removing organic sulfur bound within the coal matrix. This suggests sulfur is organically bound or present in fine pyrite not effectively separated. The investigation also shows that the sulfur concentration of treated coal is gradually lower at 0.34 weight percent as opposed to 0.36 weight percent for raw coal. When assessing a fuel's environmental friendliness in relation to possible $SO_2$ pollutant emissions, sulfur concentration is a critical component (Mekdes , 2023). Sulfur content of the coals studied in this area is less than 1%, with a variation of treated coal 0.02% from raw coal. The coals examined in this study have a sulfur concentration that is within an acceptable range according to ASTM standard, despite the fact that high sulfur content may restrict future uses of coals, especially in the production of steel. Further desulfurization methods (e.g., chemical leaching) may be required for compliance with strict emission standards. According to (Mekdes, 2023) to determine the sulfur content in the coal, the calorific value was initially estimated using a washing method based on the bomb calorimeter. The sulfur present in the coal sample was converted to sulfur dioxide that dissolved in the water to form dilute sulfuric acid. The sulfate was precipitated by treating the solution with barium nitrate ($Ba(NO_3)_2$), which resulted in the formation of barium sulfate ($BaSO_4$). The precipitate was altered while still hot, washed, dried and ignited to a constant weight. Sulfur Content: Assessed by converting sulfur to sulfur dioxide and then precipitating it as barium sulfate.

### 4.4 Calorific Values

The experimental value of calorific value for both raw and floated coal samples is determined by using the Adiabatic Bomb calorimeter in the central laboratory of the Ethiopian Geological Institute. As shown in Table-6, the obtained result of the calorific value (CV) for the raw was 4804.07Cal/g (8647.33Btu/1b.), which increases to 6418.15Cal/g (11552.67Btu/1b.) in the treated coal. The calorific value (CV) in Table 6 shows a significant improvement after the flotation process. This enhancement highlights the effectiveness of the flotation process in upgrading the quality of Ela-Hanchano coal by removing impurities and concentrating its energy-rich components.

### 4.5. Industrial and Environmental Implications

The treated coal’s calorific value (6,418cal/g) positions it as a viable energy source for cement, steel, and power industries. Reduced ash and moisture lower slag formation and transportation costs, while moderate sulfur content necessitates emission controls. This study provides a framework for optimizing Ethiopia’s coal resources, reducing energy imports and supporting economic growth.

### 4.6 Comparison with another Ethiopian coal study

Ela-Hanchano coal, located in the Konta Zone is classified as lignite to sub-bituminous coal similar to the Delbi-Moye deposit which is also composed of lignite to sub-bituminous coal. Both coal deposits are found within sedimentary basins that have developed in association with volcanic formations. The geological structure of Delbi-Moye, located in southwestern Ethiopia plateau which was influenced by the East African Rift System, coal-bearing formations interbedded with sandstone and shale (Wolela, 2007) just as the Ela-Hanchano deposit does. The coal seams alternate with sandstone, shale, and clay stone, suggesting that deposition occurred in fluvio-lacustrine settings. Whereas the volcanic formations are mostly composed of trachytes and basalts, the sedimentary formations are composed of layers of coal, sandstones, and shales. Tectonically, the formation of these coal-bearing basins is affected by faulting, especially in the Gojeb-Chida Basin, where structural activity created the conditions necessary for sediment accumulation.

# CHAPTER FIVE

# 5. CONCLUSION AND RECOMMENDATIONS

## 5.1. CONCLUSION

The study on flotation efficiency in Ela-Hanchano coal from the Konta Zone Southwestern Ethiopia was able to prove that significant improvement in coal recovery and quality was possible with the use of optimized froth flotation methods. The finer particle sizes favored high recovery rates, with the highest efficiency being about 87.58% for the undersize of 75 micrometer. The proximate analysis showed that the treated coal had significantly improved by the contents of moisture and ash had decreased with comparing to the raw coal, while those of fixed carbon and calorific value had increased to the treated coal than raw coal. Treated coal showed a reduction in moisture content from 21.54% to 2.60%, a decrease in ash content from 12.90% to 10.95%, and an increase in fixed carbon from 34.14% to 46.41%. Moreover, the calorific value of coal improved from 4,804.07 Cal/g (8,647.33 Btu/lb.) for raw coal to 6,418.15 Cal/g (11,552.67 Btu/lb.) for treated coal, making it a more efficient energy source. All these results point to the possibilities of flotation techniques for coal quality improvement, making coal a valuable product for industrial applications. Besides, the optimum dosages of collector and frother should be carefully chosen for maximum flotation performance. Based on this study the Ela-Hanchano areas have good coal market potential because nearly the coal seam is ranges between lignite to sub-bituminous.

## 5.2. RECOMMENDATIONS

Even though this study has successfully evaluated Ela-Hanchano coal’s flotation efficiency, but several aspects still require further research. In order to enhance coal recovery and quality, future research should focus on improving flotation parameters by experimenting with a wide range of reagent quantities, flotation times, and air flow rates. Future research should concentrate on developing methods to improve the Ela-Hanchano coal beneficiation process and further lower the sulfur level. Targeting both organic and inorganic sulfur more successfully may be possible with the use of sophisticated flotation reagent or the use of chemical desulfurization’s techniques. Through in depth mineralogical investigation, a better comprehension of the forms and distribution of sulfur in coal matrix would be advantageous. The strategies and financial commitments that help to expand coal beneficiation infrastructure are very critical for the full exploitation of Ethiopia’s coal resources.

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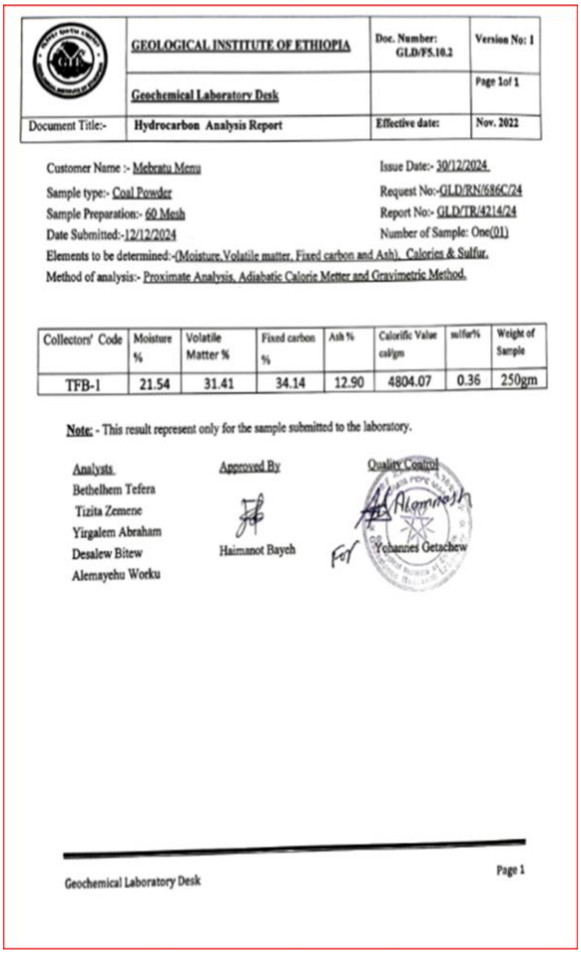
# APPENDIX

## The Ethiopian Geological Institute Laboratory Results of raw and treated coal



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| | **GEOLOGICAL INSTITUTE OF ETHIOPIA** | **Doc. Number: GLD/F5.10.2** | **Version No: 1** |
| | **Geochemical Laboratory Desk** | | **Page 1of 1** |
| Document Title:- | **Hydrocarbon Analysis Report** | **Effective date:** | **Nov. 2022** |

Customer Name :- Mebratu Menu
Issue Date:- 30/12/2024.
Sample type:- Coal Powder
Request No:-GLD/RN/686C/24
Sample Preparation:- 60 Mesh
Report No:- GLD/TR/4214/24
Date Submitted:-12/12/2024
Number of Sample: One(01)
Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash), Calories & Sulfur.
Method of analysis:- Proximate Analysis, Adiabatic Calorie Metter and Gravimetric Method.

| Collectors' Code | Moisture % | Volatile Matter % | Fixed carbon % | Ash % | Calorific Value cal/gm | sulfur% | Weight of Sample |
|---|---|---|---|---|---|---|---|
| TFB-1 | 21.54 | 31.41 | 34.14 | 12.90 | 4804.07 | 0.36 | 250gm |

**Note:** - This result represent only for the sample submitted to the laboratory.

Analysts
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Yirgalem Abraham
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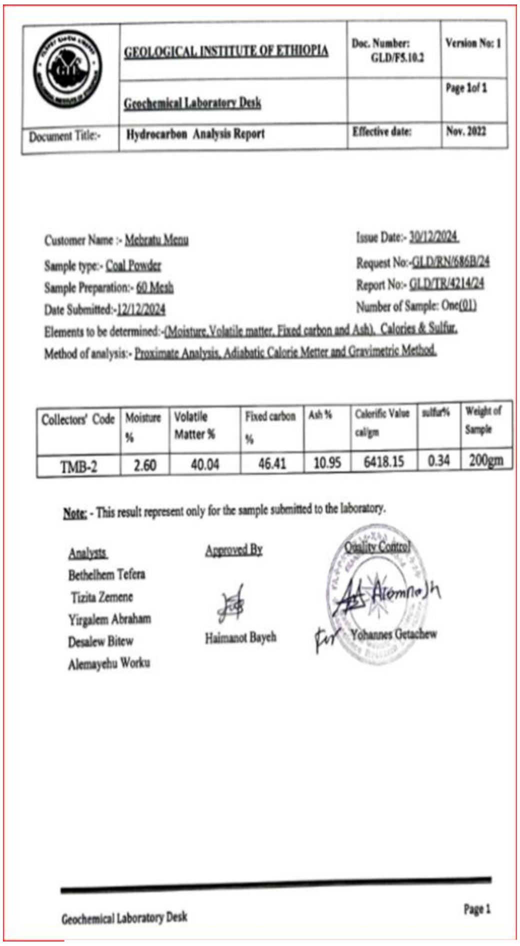
A, The result of raw coal



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Customer Name :- Mebratu Menu
Issue Date:- 30/12/2024.
Sample type:- Coal Powder
Request No:-GLD/RN/686B/24
Sample Preparation:- 60 Mesh
Report No:- GLD/TR/4214/24
Date Submitted:-12/12/2024
Number of Sample: One(01)
Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash), Calories & Sulfur.
Method of analysis:- Proximate Analysis, Adiabatic Calorie Metter and Gravimetric Method.

| Collectors' Code | Moisture % | Volatile Matter % | Fixed carbon % | Ash % | Calorific Value cal/gm | sulfur% | Weight of Sample |
|---|---|---|---|---|---|---|---|
| TMB-2 | 2.60 | 40.04 | 46.41 | 10.95 | 6418.15 | 0.34 | 200gm |

**Note:** - This result represent only for the sample submitted to the laboratory.

Analysts
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B, The result of treated coal