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

CATEGORIZATION OF COAL BASED ON COMPOSITION AND MINERALOGICAL ANALYSIS FOR EVALUATION OF QUALITY INDICATORS: A CASE STUDY OF THE BOTOR TOLAY AREA, JIMMA, SOUTHWESTERN ETHIOPIA

By
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A PROJECT THESIS SUBMITTED TO IN COMPLETION OF THE REQUIREMENT FOR THE MASTER OF ENGINEERING IN MINERAL ENGINEERING

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Addis Ababa, Ethiopia
May, 2025

ADDIS ABABA UNIVERSITY
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Approval sheet

This is to confirm that the project by Likasa Bakala, titled " Categorization of Coal Based on Composition and Mineralogical Analysis for Evaluation of Quality Indicators; A Case Study of the Botor Tolay Area, Jimma, Southwestern Ethiopia " has been submitted to meet part of the requirements for a master's of Engineering in mineral engineering. It follows the university's regulations and meets the necessary standards.

Signed by the examining committee
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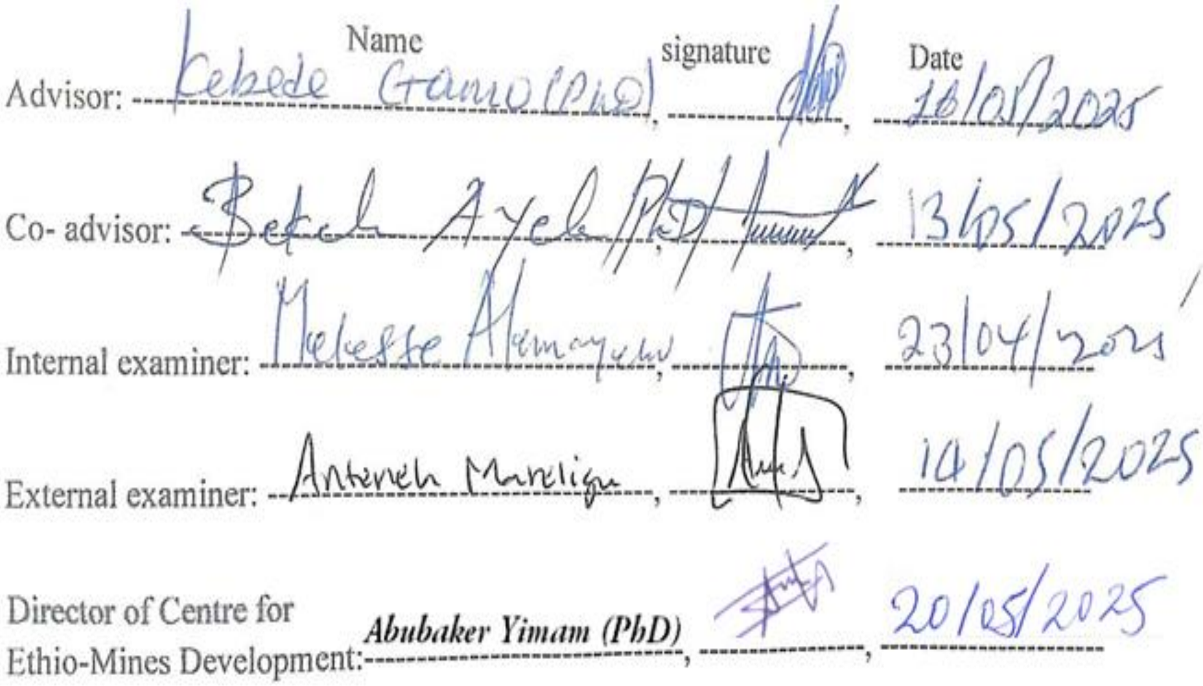

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Declaration

I hereby declare that the work presented in this project is my own original project and has not been submitted previously for any degree or qualification. This project aims to study categorization of coal based on composition and mineralogical analysis for evaluation of quality indicators. I have conformed to ethical standards and that all sources of material used for the project have been properly acknowledged.

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Acknowledgement

First, I would like to convey my deepest gratitude to the Almighty God for His unwavering love and presence along the journey of my life. I am forever grateful for His eternal guidance and support.

Next, I want to express my gratitude for the sponsorship and financial assistance provided by the Ministry of Mines and the AAiT department of the Chemical and Bioengineering, Center for Ethio-Mines Development.

I would like to express my deepest gratitude to my advisor, Dr. Kebede Gamo, for his exceptional patience, guidance, inspiration, and unwavering support throughout the course of this project. His helpful suggestions have been a major factor in this study's success.

I would also like to express my heartfelt gratitude to my co-advisor, Dr. Bekele Ayele, for his guiding suggestions, motivation and support by commenting on this project in all technical and scientific aspects. His useful ideas have contributed significantly to the success of this research.

I would like to acknowledge Ohana mining and trading PLC for support, including the providing of the coal samples, necessary data, materials, and moral support.

I would like to acknowledge all the lecturers in the Chemical and Bio Engineering department at AAiT.

Finally, I also want to thank my family for their constant motivation and support throughout education process. Special and sincere thanks to my mother Dasitu Jira, whose sacrifice and unlimited love have been the backbone of strength of my success. Her boundless patience, encouragement, and faith in my abilities instilled in me every day a sense of resolve to work for my goals with unshakeable determination. It would have been impossible for me to achieve all this without her constant guidance and encouragement. She has been my greatest inspiration, and I am dedicating this paper to her.

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Acronyms

AC ……………………..Ash Content

ASTM ………………….American Society for Testing and Materials

CV……………………….Calorific Value

FC………………………. Fixed Carbon

JCPDS……………………Joint Committee on Powder Diffraction Standards

MC……………………….Moisture Content

VM……………………….Volatile Matter

Abstract

The classification of the coal's composition from the Botor Tolay deposit and its implications for coal quality indicators are the main goals of this study. The project research employs analysis of coal samples collected from five points within the studied area, utilizing techniques such as proximate, calorific value, sulfur content, XRD, XRF, and FTIR analysis methods to determine key compositional elements. The results reveal distinct categories of coal based on their calorific value, sulfur presence, moisture content, ash content, volatile matter, fixed carbon, and fuel ratio. Accordingly, calorific value ranged from (7,406.54 to 9,783.46Btu/lb), sulfur content (0.17 to 0.21%), moisture content (1.12 to 1.46%), ash content (33.99 to 48.52%), volatile matter (19.13-21.94%), fixed carbon (30.84 to 42.88%) and fuel ratio (1.61 to 1.95%). Hence, all the studied coal samples fall within the sub-bituminous coal category based on calorific value categorization. One of the coals sample BT-1 has the highest percentage of fixed carbon (42.88%), which made it to have a high fuel ratio, enabling it to be more combustible. Major element analysis of the coal sample indicates it contains the maximum amount of SiO_2 (67.668% by wt.), and Al_2O_3 (24.194% by wt.) followed by Fe_2O_3 (4.472% by wt.) and (TiO_2 (1.296% by wt.). Functional group analysis indicated the presence of the peak of the -OH stretching vibration group and the peak in the spectra of coal found between 1100 and 400 $cm^{-1,}$ which are assigned to clay minerals such as quartz, kaolinite, and illite. The Crystal chemistry structure analysis of the coal sample revealed the presence of silicon dioxide (SiO_2) and pyrite (FeS_2), which may contribute to increased ash content.

Key words: coal categorization, quality, proximate analysis, calorific value

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Coal is a non-renewable energy source originating from ancient plants that have existed for millions of years (Anuradha, 2019). It is the fossil fuel energy resource provides energy for the industry, steel and cement uses. It was predicted that coal play a very significant role in world primary energy demand well into the future. It has been estimated that there are over 860 billion tonnes of proven coal reserves worldwide (Obaje, 2009; Samaila et al., 2020). This means that there is adequate coal to last us at minimum 118 years at existing rates of consumption.

China, India, Indonesia, USA, and Australia were considered as the top five countries by producing combined annual production of 6.35 billion tons of coal. About 3.94 billion tons, which accounts 50.8% of the world's total production is produced by China (Benintendi et al., 2020). On the other hand, five countries, mostly Australia, Indonesia, Russia, USA, and Canada are marked as the top five exporters of coal to the international markets; for example, these five countries mentioned above transported 81.1% of the entire values sold in the international markets during the year 2023 (Coal Market Update_July, 2023). Until now coal is the world's most plentiful and widely distributed resource of fossil fuel, which is 64% of worldwide recoverable fossil resources related to oil (19%) and natural gas (17%) (Osborne et al., 2023). Internationally, the main application of coal for cement production (over 90%), iron and steel production (70%), electricity generation (41%), transportation fuels, feedstock to produce chemicals, industrial-process heating, and household heating and cooking (Buchanan et al., 2014).

According to the report of the Ethiopian Institute of Geological Survey, Ethiopia's coal reserves were estimated to be 300 million metric tons. The occurrences are widely distributed throughout the country, especially in the central plateau of Ethiopia (Mush Valley Basins, Wuchale), the Northern (Chilga basin), the South-Western (Delbi-Moye, Yayu (Wittete, Achibo-Sombo, & Dabaso), and Nejo and Arjo basins (Usman et al., 2022; Wakuma & Assaba, 2017). In Ethiopia, coal has served as a source of energy for industries such as cement factories. Coal is used by the cement industry for burning the raw materials at high temperature (1450°C) in a kiln. Because of the expansion of industrial development and the country's high population growth, from time to time there is a highly increasing demand for energy where the supply of energy is limited and counterbalanced with the existing demand (Wolela, 2010;

Usman et al., 2021). Due to the high impurity and low quality of domestic coal, these factories are forced to use and depend more on imported coal by spending high foreign exchange rates to satisfy the growing demands of their industries (Usman et al., 2022). Knowing the reason for the high impurities and low quality of domestic coal may fulfill the counterbalance of existing demand.

A range of physiochemical natures, including heating value, fixed carbon content, ash melting temperature, sulfur content, and presence of other impurities, is recommended to be evaluated in the selection of coals for a given application (Yi et al., 2017). Each of these characteristics changes the environmental impact and burning efficiency of coal. The classification process includes the examination of coal samples to ascertain their physiochemical nature. It is very essential to decide the composition of the coal in order to forecast the products and amount of energy that are emitted during the burning process, apart from deciding the value of coal. Therefore, categorizing the coal composition is an effective approach to determining coal quality for sustainable and appropriate industrial applications.

Proximate analysis is the method that was determined to be useful in deciding the yield of products, which are produced when coal is heated under a set of standard conditions and provides the composition in relations of moisture, ash, volatile, and fixed carbon (Yi et al., 2017). Ultimate analysis is used to describe the content of important chemical elements such as hydrogen, carbon, nitrogen, sulfur, and oxygen. Coal categorization uses Fourier-transform infrared spectroscopy (FTIR) to identify functional groups within coal samples, which gives information regarding their chemical makeup and characteristics (Saikia et al., 2007a); X-ray fluorescence (XRF) to analyze the composition of the coal samples' constituents; and X-ray diffraction (XRD) to find out the mineral content of the coal (Sonibare et al., 2010). Understanding the compositional and mineralogical nature of the coal source becomes critical with growing needs for high-grade coal for diverse industrial uses. Though the study area (Botor Tolay) coal deposit is identified by (Jisan & Rao, 2019), composition and quality remain unstudied so far. Hence, the present study aims to categorize the coal based on composition and mineralogical analysis for evaluation of quality indicators in case of Botor Tolay coal deposit, Jimma, Southwestern Ethiopia by linking proximate analysis and analytical techniques.

1.2. Description of the study area

1.2.1. Location and accessibility

The study area is located at a distance of 113 km southwest of Addis Ababa through Welkite town by main asphalt road, and then 70 km north of Welkite town to Botor Tolay woreda by gravel road, in Oromia regional state, Jimma zone. The targeted area is bounded between the geographic coordinates of ’329483’ N–’329656' N and ‘913301’ E–‘913470' E latitude and longitude, respectively, with an elevation of 1498 m above sea level near Gibe River streams. The accompanying figure (1) depicts the study area's accessibility and location as: A) Map of Ethiopia, B) map of Oromia region, C) map of Botor Tolay district, D) location map of study area.

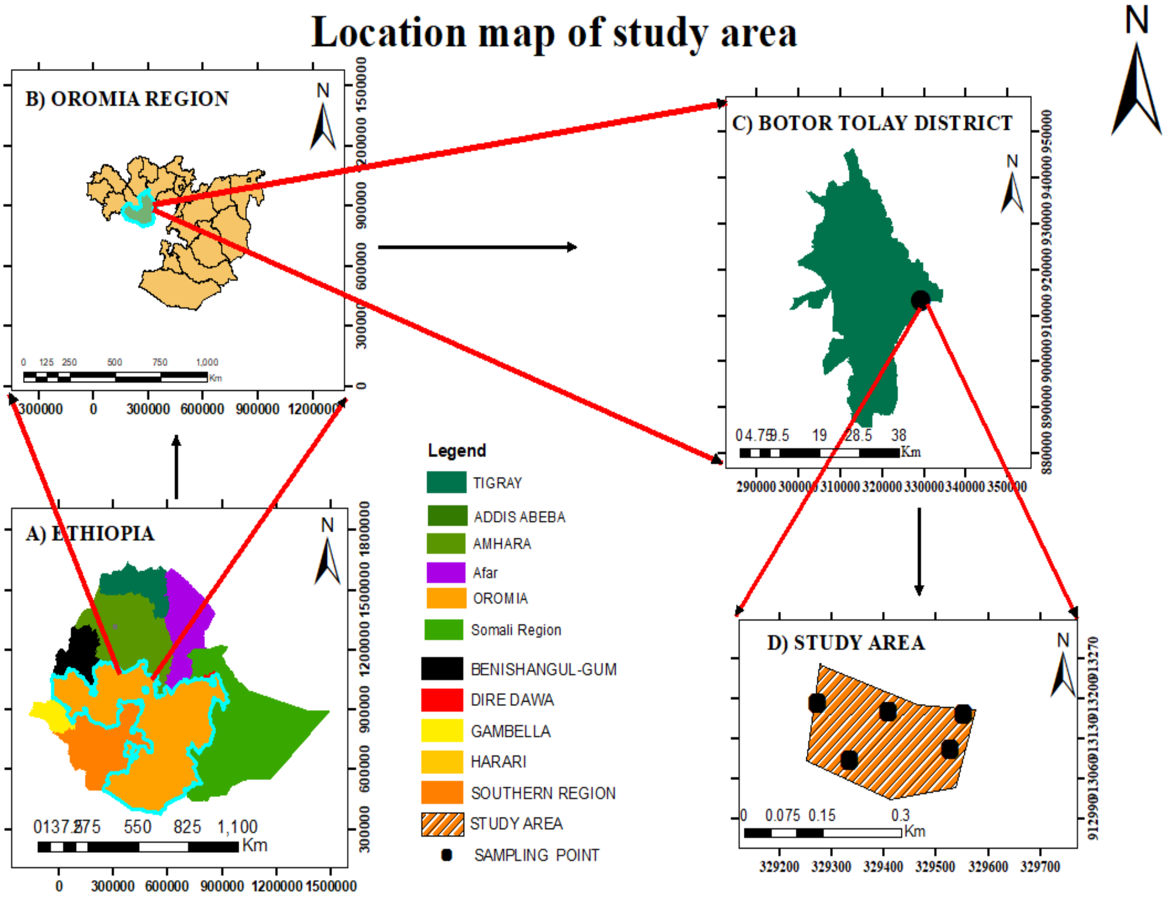

Figure 1: Location map of the study area

1.2.2. Physiography

The topography of the land is characterized as a stream valley and the Gibe River on the north, and southwest ridge forming hillsides; the south is steepened (high contour), and the north hill is comparatively steepened and gentle on the upper surface area. The physiography of the study area indicates rugged topography with parallel ridges and varying heights of 1110m to 1601m above mean sea level. The low-lying regions within the basin are comprised of basaltic ridges, while trachytic hills aligned in a NE-SW direction were observed. These hills are deeply dissected by basalt-floored within Gibe river streams. In the western part area, hills and mountain ridges dominate the landscape as shown in Fig.2.

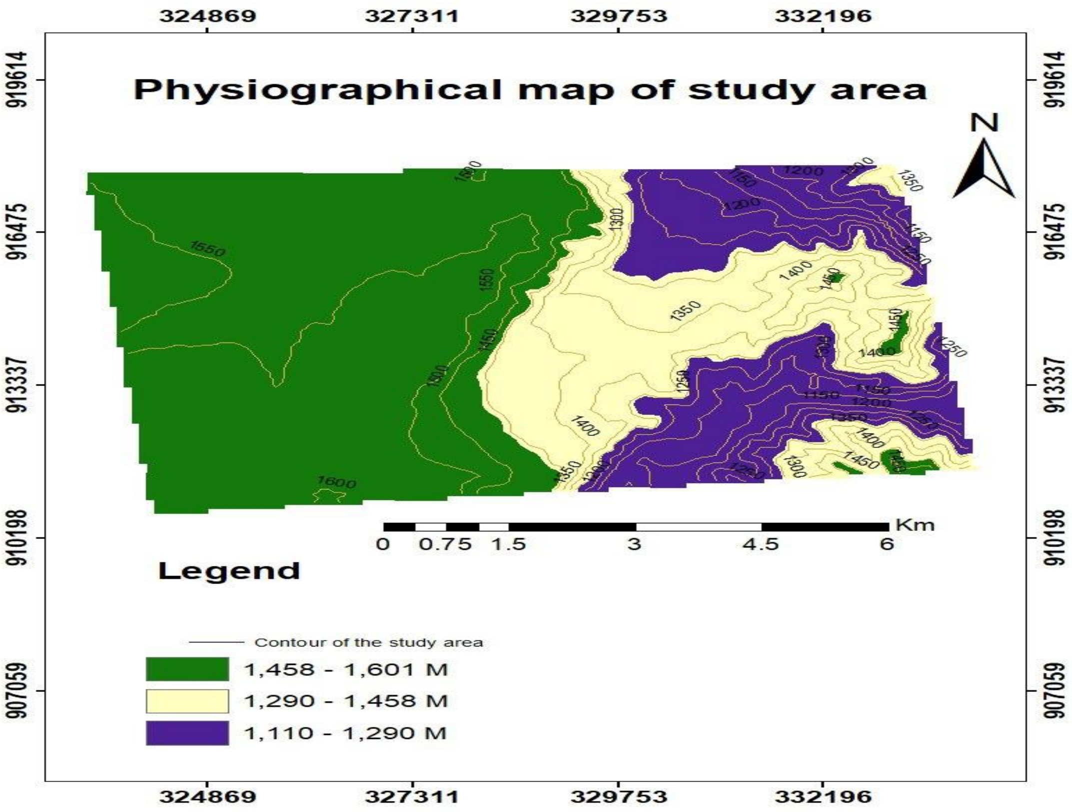

Figure 2: Physiographical map of study area

1.2.3. Climate condition and Vegetation

Ethiopia has a diverse climate and landscape, ranging from equatorial rainforest with high rainfall and humidity in the south and southwest, to the Afro–Alpine on the summits of the Simien and Bale mountains to desert-like conditions in the northeast, and southeast lowlands (Wubaye et al., 2023). Overall, Ethiopia is considered largely arid but exhibits a high variability of precipitation Ethiopia’s climate is broadly divided into three zones. 1) The alpine vegetated cool zones (Dega) with areas over 2,600 meters above sea level, where temperatures range from near freezing to 16°C; 2) the temperate woina dega zones, where much of the country’s population is concentrated, in areas between 1,500 and 2,500 meters above sea level where temperatures range between 16°C and 30°C; and 3). The hot Qola zone, which encompasses both tropical and arid regions, has temperatures ranging from 27°C to 50°C.

Similar to most of the southwestern plateau of highlands of Ethiopia, the project area is characterized by warm and humid subtropical climatic conditions. Two seasons of rainfall are known in the region, namely: the summer season, June-September, and the spring season, March-Aprill, with an annual rainfall of 1,600mm distributed in two seasons, with dry seasons of 6 to 7 months. The warmest season, 25°C is from November to March; the mean temperature on the plateau is 5°C. The annual average precipitation is 220.48 mm, the annual maximum precipitation is 430.1 mm, and the monthly maximum precipitation is 48.2 mm. The natural vegetation is exceptionally diverse; thick tropical forest in the north passes to acacia trees, thorny bushes, and tall elephant grass cover in the south (Wubaye et al., 2023).

1.2.4. Geology of the study area

According to the Geological Survey of Ethiopia (2012), the report indicated that the general topography of the Jimma Zone was an indicator of different geological processes, with large areas having been formed during the Cenozoic era. Quaternary alluvial deposits and basalts dominantly cover the area and intermediate trachyte flows. It lies on the volcanic rock of the Tertiary period, essentially basalt and overlain by the Trap formation that consists of medium to acidic lava. This geological formation means that the Jimma Zone has great potential for mineral resource development. The Botor-Tolay coal deposit, which is found in the Jimma Zone, is covered with diverse rock types that are prospective for depositional environment information and the constraints that might arise in coal mining.

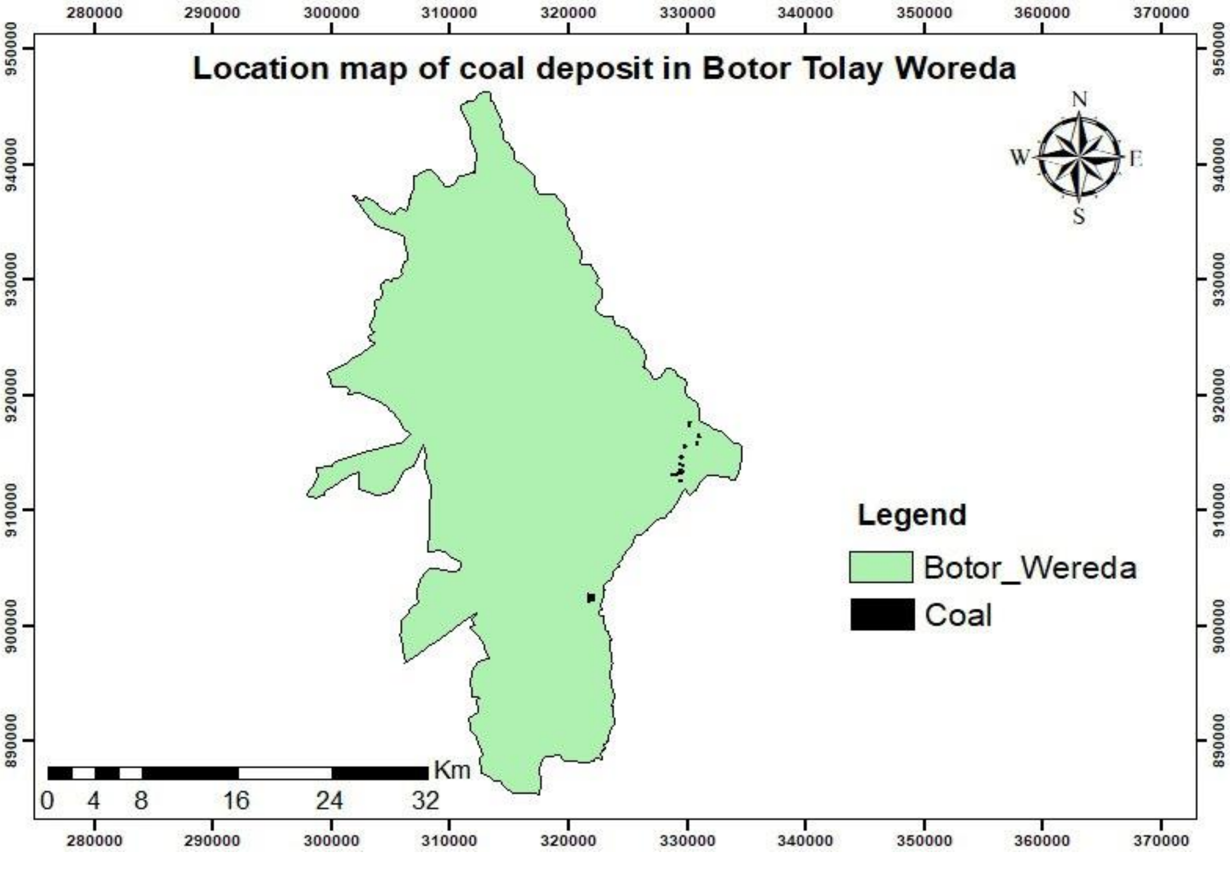

Figure 3: Location map of Coal deposit in Botor Tolay woreda

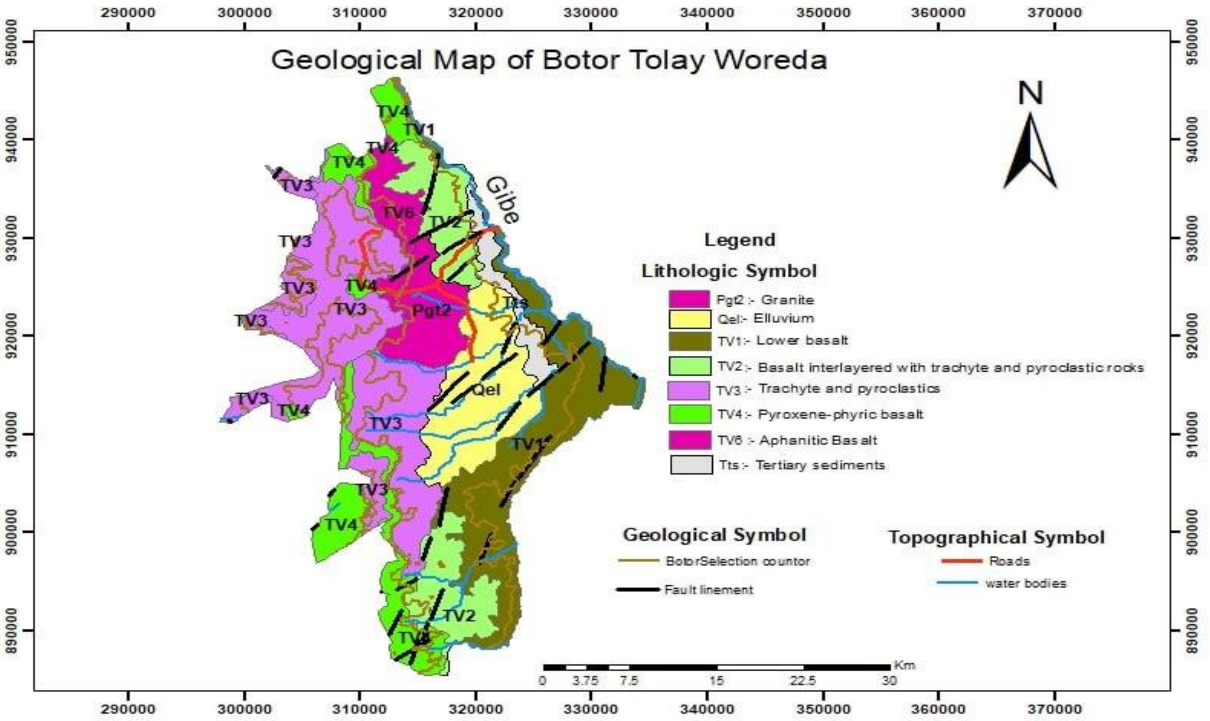

Figure 4: Geological map of study area

Dominantly, Tertiary volcanic and coal-bearing sedimentary rocks underlie the study area. Fractured, fissured, and highly fractured aphanitic basalt is the most dominant rock type, highly affected by intense vertical and horizontal weathering, resulting in slightly to completely weathered material. The lithological units identified include:

Trachyte: This unit is found only in the top part, though at some places it occurs at lower elevations and directly overlies sedimentary units due to structures. This unit exists both as bedrock and, in some places, as weathered, transported blocks. This unit generally displays a light grey to dull whitish-white color, and texturally it is fine, but in a few places it shows fine to medium-grained and has moderately jointed blocky fractures. It shows deep weathering, and the unit becomes highly oxidized and kaolinized. Based on field observation, the unit is classified into the range from intermediate to felsic volcanic rock (Fig. 5).

Figure 5: Trachyte and Tertiary sedimentary rock

Tertiary Sediment: This unit occurs mostly as a layer intercalating with the mudstone in different places; it is dark grey colored, weakly bedded and laminated, friable, and fissile like a sheet (Fig. 5). Coal seams of varying thickness were discovered in the gently sloping sedimentary rocks of the study area. The seams were almost horizontal and flat. The coal found in the studied area is classified physically as black grey to shiny. The seam's boundaries are defined by mud at the bottom and sand and mudstone at the top. At some places in the study area, coal is seam bound between volcanic lithology at the top and bottom. Therefore, it is a kind of inter-trapean coal.

Basalt: It occurs as gentle slopes and steep cliffs form and unconformable overlie the Precambrian rocks. It is greyish black to black and commonly aphanite to locally porphyritic and amygdaloidal, with amygdules filled by calcite and zeolite. Its bottom part is largely porphyritic with phenocrysts of dominant olivine and rarely pyroxene, which lie within aphanitic to fine-grained groundmass (Fig. 6).

Figure 6: Basalt

1.3. Statement of problem

The mineralogical composition and coal properties are quite crucial in ascertaining the quality of coal, which directly affects its environmental impact, economic viability, and combustion efficiency. The former investigators ascertained the coal potential in Ethiopia (Wolela, 2008; Wakuma & Assaba, 2017; Usman et al., 2021), but the detailed Ethiopian coal potential reserves are not well studied yet. Though the Botor Tolay, Southwestern Ethiopia, coal deposit is identified by (Jisan & Rao, 2019), there is limited understanding of the specific coal quality indicators derived from the mineral content and chemical composition of local coal deposits by linking analytical techniques and proximate analysis. This lack of comprehensive analysis makes the exploitation of the coal deposits uneconomical for industrial and energy usage. The lack of stipulated classification techniques based on composition and mineralogical analysis also makes it challenging to establish the feasibility of the coal for various applications like power generation and industrial processing. The likely environmental impacts of utilizing low-grade coal further highlight the need for a comprehensive study. Therefore, the study aim to address the gap in study by linking proximate analysis, Calorific Values, and analytical techniques (XRD, XRF, and FTIR) for quality evaluation in the Botor Tolay area that previous studies overlooked.

1.4. Objective

1.4.1. General objective

The main objective of this study is to categorize the coal based on composition and mineralogical analysis for evaluation of quality indicators in case of Botor Tolay coal deposit, Jimma, South Western Ethiopia.

1.4.2. Specific objective

- To determine the proximate analysis of the Botor Tolay coal resource
- To calculate the calorific value, which measures heat energy of the Botor Tolay coal resource
- To identify the types and amount of mineral content present in a Botor Tolay coal resource

1.5. Significance

This research project has valuable insights into the challenges posed by misunderstanding regarding the categorization of coal composition and how it impacts various measures of its quality. The results of this study are expected to provide guidelines for improving coal quality and classifying coals systematically with physical and chemical characteristics. Of particular significance are

- Categorizing coal based on its composition allows suppliers to optimize resource usage and design a mining process that extracts the most valuable qualities.
- Using categorized coal significantly lowers the risk of environmental compliance issues.
- Providing information about coal composition raises stronger relationships with customers and suppliers.
- Through categorization, the suppliers can develop effective pricing strategies based on the quality of their coal.
- Provides guides for customers who frequently look for specific coal grades for their operations.

1.6. Scope of study

The study’s goal was to classify coal compositions and establish useful insights for stakeholders in the coal sector. Laboratory experiments were conducted by using coal samples collected from the Botor Tolay coal deposit. The research was supported by the classification methodologies provided by the American Society for Testing and Materials (ASTM) standard. The research employed various analytical techniques, including proximate analysis, calorific value determination, sulfur content measurement, and advanced techniques including X-ray diffraction technique, X-ray fluorescence, and Fourier transform infrared spectroscopy. The study systematically evaluated key parameters such as moisture content, ash content, fixed carbon, volatile matter, elemental composition, and mineral composition and facilitated the characterization of the coal deposit's energy potential and quality implications.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

Coal is an organic fossil fuel and sedimentary rock containing, but not limited to, carbon, hydrogen, sulfur, and nitrogen along with traces of other elements such as methane and mineral matter in its pore system. Carbonaceous, solid, brittle, and flammable rock is created when vegetation is broken down and altered by pressure, temperature, and compaction (Jovanovski et al., 2023; Samaila et al., 2020; Usman et al., 2021; Wakuma & Assaba, 2017). Coal is used globally for a variety of purposes, including generation of electricity, steel and cement production, and household energy needs. Cement factories in Ethiopia are the largest consumers of coal, while other industrial uses such as pulp and paper, gypsum, textiles, ceramics, leather, and pharmaceuticals utilize smaller amounts of coal. Coal is also valued due to its relatively low price, ease of use, storage, and transportation, and its utilization does not typically lead to geopolitical tensions (Genetu & Kebede, 2024a).

2.2. Formation of coal

Overall, the greatest of the coal (and the additional two fossil fuels, natural gas and oil) extracted today is supposed to have been created from plants that developed in and neighboring to swamplands in warm, humid provinces hundreds of millions of years ago (Jovanovski et al., 2023). Coal is a remnant of firewood with a temperately high energy density that is formed when organic and inorganic material deposits and then undergoes a transformation process over geological time (Zivotic et al., 2024). Several times in the geologic past, microbes converted the peats from these condensed forest plants growing in low-lying wetlands that stayed wet most of the time into peat, which is partially decomposed plant material that resembles soil. This organic plant material eventually formed into coal.

There are three main sources of evidence (Jovanovski et al., 2023) that coal resulted from plants. These are: 1) the first has to do with lignite, which is the lowest rank and often contains recognizable fragments of plants. 2) Plant fossil-leaves and stems-in the form of imprints and burnt films in sedimentary beds above and below, as well as beside coal seams. 3) The third proof is connected with the fact even high-rank coal can contain plant ancestor material. In general, coal is accumulated based on pressure and heat, which acts on the plant remains as they fall deeper and deeper over millions of years, providing the energy that was based on its deposited depth. The various coal stages of formation include lignite, bituminous, and anthracite, as shown in Fig.7. These different stages are based on conditions that the plant and fossil remains are subjected to after burial, for example, increased heat and pressure, to move from the lower to higher coal ranks.

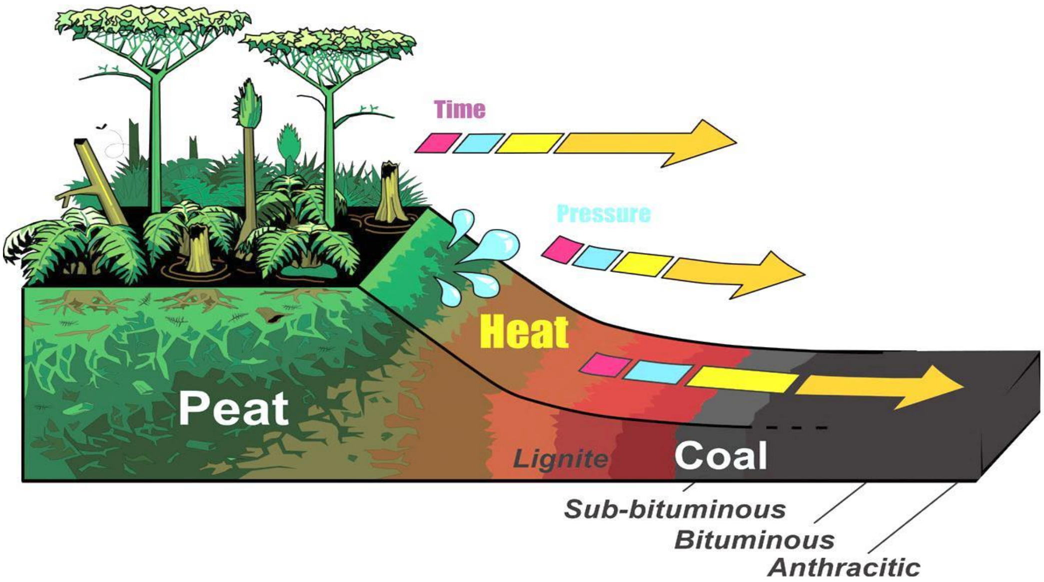

Figure 7: Coal formation with increasing rank

2.3. Classification of coal

A coal classification system is used in describing, selling, and purchasing coals. Given the fact that coals around the world vary greatly, there is a great necessity for a coal classification system. According to the American Society for Testing and Materials Standard (ASTM D-388), coal is classified into four major types. These include lignite, sub-bituminous, bituminous, and anthracite coal (Suárez-Ruiz et al., 2019). The types and quantities of carbon that coal contains, together with the heat energy it gives off, may be used to grade the coal. The rank of the coal resources is determined by the quantity of heat and pressure that the plants were subjected to over time, as indicated in Table 1.

Table 1: Classification of coal by rank (ASTM D388-23)

Class/Group		Sub-groups of coal	Methods of determining rank (dmmf)(U.S ASTM)						Agglomerating
			Fixed carbon limit (%)		Volatile Matter limit (%)		Calorific Values (Btu/lb)		
			≥	<	>	≤	≥	<	
High rank coal	Anthracite	Meta-anthracite coal	98	--	--	2	--	--	Non-agglomerating
		Anthracite coal	92	98	2	8	--	--	
		Semi-anthracite coal	86	92	8	14	--	--	
Medium coal rank	Bituminous	Low volatile bituminous coal	78	86	14	22	--	--	Commonly agglomerating
		Medium bituminous coal	69	78	22	31			
		High volatile bituminous coal A	-	< 69	-	< 31	> 14,000	--	
		High volatile bituminous coal B	--	--	--	--	13,000	14,000	
		High volatile bituminous coal C	--	--	--	--	11,500	13,000	Agglomerate
Low coal rank	Sub-bituminous	Sub-bituminous coal A	--	--	--	--	10,500	11,500	Non-agglomerating
		Sub-bituminous coal B	--	--	--	--	9,500	10,500	
		Sub-bituminous coal C	--	--	--	---	8,300	9,500	
	Lignite	Lignite coal A	--	--	--	--	6,300	8,300	
		Lignite coal B	--	--	--	--	5000	< 6,300	

Peat is the primary step in the coal formation process. In this, the decompositions of dead vegetable plant material are mostly oxidized to form carbon dioxide and water. On the other hand, if plant material is accumulated underwater without oxygen, then only partial decomposition of the organic substance takes place. So peat includes a high quantity of water and a very low value of carbon number with more impurity and sufficient volatile matter (Usman et al., 2022; Jovanovski et al., 2023).

Lignite has a brown, blackish appearance, and it is characterized by its soft texture. The name "lignite" comes from the Latin word meaning wood, "lignum," since it contains remains of the wood fiber. It is the youngest, poorest-quality coal and has small deposits with low energy content. Lignite is very brittle with a high moisture and ash content. It contains the lowest amount of carbon, between 20-40%, and the calorific value is low at less than 8300 Btu/lb, as shown in Table 1. The chemical formula for lignite is $C_{180}H_{145}O_{13}N_5S$. Lignite coal contains high levels of nitrogen and sulfur, which may be unhealthy for human health (Simon, 2019). Further, the combustion of lignite coal releases a high amount of particulate matter, which contributes to environmental pollution and erosion of heat exchangers (Usman et al., 2021).

Sub-bituminous coal ranks midway between bituminous and lignite coal in terms of calorific value; that is, it includes coals of lower calorific value bituminous but higher calorific values than lignite coal. Sub-bituminous coal belongs to the younger coals and is about 251 million years old (Jovanovski et al., 2023). It contains some 40-45% carbon and possesses a heat content of about 8,300 to 11,500 Btu per pound (Table 1). One advantage sub-bituminous coal has is that it normally contains much less sulfur than lignite, making it more agreeable to use.

Bituminous coals contain 45 to 86% carbon and generally have considerably higher calorific value ranges of between 10,500 and 14,000 BTU/lb compared to lignite. This type of coal is produced at high temperatures and pressures, and because of its high carbon content and low moisture content, it is perfect for producing coke, cement, and electricity (Zivotic et al., 2024).

Anthracite is the dark black type of coal of the highest quality. It is extremely hard and has low moisture and 95% carbon content almost (Cho & Jull, 2023). The formation of biomass buried 350 million years ago usually forms anthracite, the oldest type of coal. Anthracite contains more energy density of 33 MJ/Kg than other coals; it is used for space heating. It burns longer than wood, which makes it attractive for use in home heating stoves (Jovanovski et al., 2023). The use of anthracite coal is necessary and useful, especially in the current energy crisis in the world.

2.4. Characterization of coal composition

Coal remains a primary source of energy in almost every country, which is transformed into heat and electrical power through many diverse technologies for a wide range of uses. It therefore follows that the monitoring of coal quality is one important undertaking that needs informing from the knowledge of coal's physical and chemical character (K.Verma et al., 2010; Wakuma & Assaba, 2017). Mostly, physicochemical determination and characteristics of coal data analysis include three parameters (Behera et al., 2018; Dhawan & Sharma, 2019): (a) the proximate analysis (that includes ash content, volatile matter, moisture content, and fixed carbon); (b) the ultimate analysis (such as hydrogen, carbon, nitrogen, oxygen, and sulfur); and (c) the coal’s heating value (CV).

2.4.1. Proximate analysis

The proximate analysis entails establishing the weight percentage of the moisture, ash, volatile matter, and fixed carbon present within the coal. Primarily, the moisture content indicates the amount of water within the sample, usually described in terms of total weight percentage (Rao & Anuradha, 2019). Higher-rank coals often have lower values of moisture content, whereas lower-rank coals often have higher moisture content due to physically and chemically absorbed water (Wakuma & Assaba, 2017; Usman et al., 2021).

Volatile matter denotes the components of the coal that are free as a gas, such as methane, carbon dioxide, water vapor, and other organic compounds that are released when the coal is excited to higher temperatures in the absence of air. The volatile content of coal increases its calorific value and its energy efficiency (Ankur & Amarendira, 2022). Coals that have higher volatile matter indicate better ignition properties and can burn more (Mahanta et al., 2024). However, it affects how easily coal can be burned and how quickly it will combust.

Ash is the amount of residual material from coal and refers to the portion that does not burn. Generally, it denotes the mineral matter that is left behind after carbon, oxygen, sulfur, and water have been taken out by combustion, in which the quality of coal is represented (Rao & Anuradha, 2019). The presence of higher amounts of ash reduces the efficiency of combustion and capacity of burning along with an increase in handling costs, causing considerable slagging. In utilizing coal, the amount of ash and behavior at high temperatures determine the type and design of ash handling system adopted. Coal ash turns sticky at high temperatures and subsequently turns into molten slag. As high proportions of impurities lower the efficiency of coal, a high proportion of ash lowers the quality of coal (Usman et al., 2022).

Fixed carbon is the carbon that remains in the substance after volatile materials have been disqualified. This is quite different from the total carbon content in carbon, which differs from fixed carbon as such volatile hydrocarbons miss some of their carbon. As such, with the advancement of the coal rank, one normally points out an increase in fixed carbon content (Rao & Anuradha, 2019).

2.4.2. Sulfur content

The sulfur content of coal varies significantly with the nature and origin of the fossil deposits (Constantí et al., 1994; Samaila et al., 2020). The use of coal for energy production and in various coal conversion processes is indeed limited by the sulfur presence in coal. On combustion of coal, sulfur mainly present within the coal combines with the oxygen to produce sulfur dioxide (SO_2). This results in air pollution and causes acid rain. Acid rains through SO2 have negative implications for agriculture and also upset ecological balances (Fatma & Ahmet, 2023). The presence of sulfur in coal also reduces the quality of metallurgical coal (Klein et al., 1994; Samaila et al., 2020). For analyzing the coal quality, sulfur is the predominant element due to the higher quantity of sulfur, which would create risk for technological application and environmental impact. The high content of sulfur in coal reduces the heating value of combusted coal by forming high ash of sulfur contents in the forms of barite ($BaSO_4$), galena (PbS), and gypsum ($CaSO_4.5H_2O$) (Usman et al., 2022). Therefore, determining sulfur content in coal plays a crucial role in its categorization and quality assessment.

2.4.3. Calorific value

Calorific values of coal establish its energy content. It depends upon its moisture content and chemical composition. The gross calorific value is the most essential parameter in evaluating the economic feasibility of coal (Xiu-Xiang et al., 2009; Ankur & Amarendira, 2022). The energy content of coal is directly indicated by its calorific value. Higher calorific value make coal more economically attractive for industrial processes and power production because they permit the extraction of more energy from a given amount of coal.

2.4.4. Applications of coal

Coal has several crucial applications around the world. The most significant applications of coal are electricity generation, steel production, cement manufacturing, and as a source of energy for households. It is applied in several chemical and pharmaceutical industries and paper manufacture, and also several chemical products can be yielded from the by-product of coal, such as various chemicals (phenol, benzene, naphthalene, etc.), that can be yielded from refined coal tar after the gasification and combustion process (Gupta et al., 2013).

For electric power generation: Currently, coal has provided almost 40% of the world's electricity demand. Coal has been a reliable source of electricity generation for the majority of developed and developing countries. As per the World energy resource report, the primary consumers of coal are in China, India, the USA, and others, who are the biggest consumers of coal in the world. In addition, businesses and industries with their own power plant and electric utility companies consume coal to produce electricity, and power plants custom coal to produce steam.

For steel making: Global steel production is dependent on coal; 74% of steel output today depends on coal as a source of energy. Coal is heated in hot ovens to make coke, which is used to smelt iron ore into wanted iron for steel production.

For household applications: Coal is being used as a domestic source of energy for residential and small-scale industry (household cooking and industrial process heat) and exists in the form of direct burning or coal briquettes. Poor rural households in China, South Africa, India, and other nations are using coal as a domestic source of energy. Coal is an inexpensive fuel and provides double utility: it warms the home and allows for cooking to be performed in the same appliance, with a single fuel.

Cement Industry: Coal serves as a source of energy in the cement industry, which is the most vital commodity in the bridge, building, dam, road, and airport construction business. Cement is manufactured through the fusion of silica, calcium carbonate, alumina, and iron oxide under high temperature in the kiln for melting the raw material (Dianshi et al., 2018). Coal is employed in the cement process in two stages: first in a precalciner stage to use it to produce calcium oxide and carbon dioxide from calcium carbonate with coal heat value >4000 kcal/kg. The second stage of coal use is in a kiln (main burner) for the aim to producing clinker by using fine coal above a calorific value of 5000 kcal/kg (1400–1450 °C). For example, to produce a ton of cement, one requires about 200 kg of powdered coal (Usman et al., 2021). Various industries have their own requirements for coal quality during their processing, as shown in Table 2**.**

Table 2: Requirements of coal quality for various plants / industries (Meshram et al., 2015)

Characteristics	Metallurgical grade	Sponge iron plant	Thermal power plant	Cement industries [IS 12770:1989]
Moisture	Max. 10%	6%	Max. 8–12%	Max. 8%
Volatile matter	20–35%	Min. 30%	Min. 19%	Min. 24%
Ash	Should be 10%	22–25%	Max. 34%	Max. 24–27%
Sulfur	0.6%	Max. 1.0%	Max. 0.8%	Max. 0.8%

2.5. Coal occurrences in Ethiopia

The coal occurrences in Ethiopia are studied by several researchers, producing several reviews and classifications (Wolela, 2008; Abraham, 2018b; Anuradha, 2019; Demeke F. Tegegne, 2019; Ankur & Amarendira, 2022; Usman et al., 2022; Genetu & Kebede, 2024a). Accordingly, the majority of Ethiopian coal fields were implied to fall into the lignite class, but currently, sub-bituminous coal potential is held within the interbedded Cenozoic volcanic, while some of them lie between the mesozoic continental clastic and the Cenozoic volcanic. Additionally, in some cases, the coal is held between the Precambrian basement rocks and the Cenozoic volcanic. The reconnaissance surveys have confirmed once again that a coal deposit is present in different regions of Ethiopia. In some places, the coal seam is deposited in Inter-Trapean and Pre-Trapean volcanic geological environments and fluvio-lacustrine and paludal environments in exposed grabens and half-grabens along NNE-SSW and NNW-SSW fault systems. The Ethiopian coal lignite deposit can be grouped majorly into intra-Trapean lignite (Arjo and Nejo Type) and inter-Trapean lignite (Chilga Type) (Assefa & Saxena, 1984). These show the most significant coal deposits are mostly found in the inter-Trapean geological setting. However, some coal and coal bearing sedimentary of variable thickness were in sandstone-coal-shale and mudstone-coal-shale formations. In comparison to the others, Ethiopian coal reserves in the form of Inter-Trapean coal are substantially more common.

Ethiopia's southwestern and central plateaus are known for their coal occurrences intermingled with trap volcanic with a total amount of 297 million tons, and their distribution in significant amounts is well recognized and identified from the Delbi-Moye, Lalo-Sapo, Yayu, Sola, Chida, Chilga, Mush Valley, Wuchale, and Nejo basins (Wolela, 2008).

The Ethiopian maps of coal occurrences and distribution (Fig.8) and geographical distributions of Ethiopian coal and oil shale are shown in Table 3.

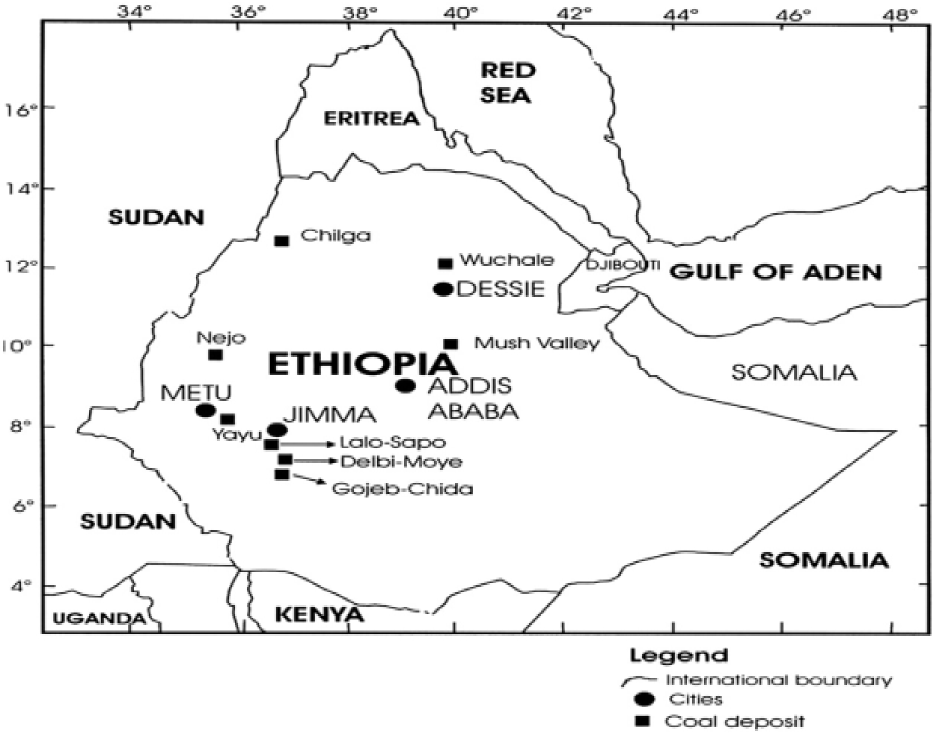

Figure 8: Ethiopian maps of coal occurrences and distribution (Wolela, 2008)

Table 3: Geographical distributions of Ethiopian Coal and oil shale (Wolela A., 1991)

No	**Area**	**Map sheet no.**	**Admini strative region**	**Geological Setting**	**Physography and tectonic setting**	**General Classification**	**Paleo - environment**
1	Ancober	NC 37-11	Shoa	InterTerrapean	Rift escarpment	Humic	Lacustrine
2	Arjo Getema	NC37-9	Wollega	InterTerrapean	SW Plateu		Lacustrine
3	Chida	NB37-1	Keffa	InterTerrapean	SW Plateu		Fluvio Lacustrine
4	Chilga	Nd37-13	Gonder	InterTerrapean	Sw Platau Within Tena rift	Mixed coal	Fluvio lacustrine
5	Debre Birhan	NC37-11	Amhara	InterTerrapean	Central Plateau	Humic	Lacustrine
6	Debre libanos	NC37-10	Amhara	InterTerrapean	SW plateau	Humic	Lacustrine
7	Delbi	NC37-1		Inter-Trappean	SW plateau	Humic, sappropelic and Kerogen I	Lacustrine
8	Dessie	NC37-13	Wollo	Inter-Trappean	Rift escarpment	Humic coal	Lacustrine
9	Dirre Dawa	NC37-12	Harar	Inter-Trappean	SE Plateau	Humic coal	Fluvitaile
10	Fiche	NC37-10	Shoa	Inter-Trappean	Central Plateau	Humic coal	Lacustrine
11	Hunda Bilisumma	NC37-18	Harar	Inter-Trappean	Rift Escarpment	Humic coal	Lacustrine
12	Jiren	NC37-1	Keffa	Inter-Trappean	SW Plateau	Humic coal	Lacustrine
13	Shakiso	NC37-10	East Guji	Inter-Trappean	SE Plateau	Humic	Lacustrine
14	Kindo Halale	NC37-6		Inter-Trappean	Rift Escarpment	Humic	Fluvitile
15	Lalo	NC37-1	Wollega	Inter-Trappean	Sw Platau	Humic, mixed coal and oilshale	Fluvio lacustrine
16	Mandi	NC37-12	Wollega	Pre volcanic	Sw Platau	Humic	Fluvio lacustrine
17	Mersa	NC37-3	Wollo	Inter-Trappean	Sw Platau	Oilshale	Fluvitile

18	Mojo	NC37-15	Shoa	Inter-Trappean	Sw Platau Within Tena rift	Humic coal	Lacustrine
19	Morka		Sidama	Inter-Trappean	Rift escarpment	Humic coal	Fluvitile
20	Moye	NB37-1	Illubabor	Inter-Trappean	Central Plateau	Humic coal	Lacustrine
21	Mugher	NC 37-10	Shoa	Pre volcanic	SW plateau	Humic coal	Fluvio-lacustrine
22	Mush valley		Shoa	Inter-Trappean	Rift escarpment	Humic coal	Lacustrine
23	Nejo	NC37-12	Wollega	Pre volcanic	SE Plateau	Humic coal	Lacustrine
24	Sola	NB37-1	Keffa	Inter-Terrapean	Central Plateau	Humic coal, oilshale	Fluviolacustrine
25	Soyoma	NB37-8	Keffa	Inter-Terrapean	Rift Escarpment	Humic coal, oilshale	Fluviolacustrine
26	Waka	NB37-1	Keffa	Inter-Terrapean	SW Plateau	Mixed coal	Fluviolacustrine
27	Wuchale	NC37-13	Wollo	Inter-Terrapean	SE Plateau	Humic coal	Lacustrine
28	Hababo Guduru		Horro Guduru, Wollega	Inter-Terrapean and Pre Volcanic	Rift Escarpment	Humic	

CHAPTER THREE

3. Materials and Methods

3.1. Materials

3.1.1. Apparatus and instruments

The apparatus and instruments used in this study were a Jaw crusher (RoHs53743) Fig. 5A, Hammer mill (RETCH 56402) Fig. 5B, Sieve shaker with different mesh sizes (Fig. 5C), Electronic balance (AUW 320) Fig. 5D, Muffle furnace (XFM-F9) Fig. 5E, Universal Hot Oven (Jaico Fisher Scientific 40GCEMD, India) Fig. 5F, Desiccator (Fig.5G), and Silica Crucible (Fig. 5H) and they are available at Addis Ababa Institute of Technology (Mechanical Operation Laboratory). An adiabatic bomb calorimeter was available at the Geological Survey of Ethiopia (Central Laboratory), XRF (Geological Survey of Ethiopia, at the Chemical and Construction Industry Input Research Center), XRD, and FTIR (at Addis Ababa University chemistry department inorganic laboratory).

Figure 9: Used laboratory equipment: A) Jaw crusher, B) Hammer mill, C) , Sieve shaker, D) Electronic balance, E) Muffle furnace, F) Universal hot oven, G) Desiccator, H) Silica crucible

3.2. Methods

3.2.1. Sample collection and preparation

Five representative coal samples (BT-1, BT-2, BT-3, BT-4 and BT-5) were collected from open-pit coalmines in the study area. Coal samples weighing 1.5 kg were gathered in an airtight aluminum pack for each and exploited randomly with some interval as an impartial representative of the group with an equal chance of getting selected. To prevent sample oxidation during preparation, the coal samples were stored in airtight plastic bags. Finally, the sample was transported from Botor Tolay to the Addis Ababa Institute of Technology for investigation. The samples were prepared using the crushing, milling, and sieving techniques specified by ASTM-2013. Jaw crushers were used for the initial steps of bulk size reduction, followed by hammer mills and sieve shakers to select coal samples with a particle size of less than -125 µm for laboratory analysis shown in the figure below.

Figure 10: Photo taken from open-pit coalmines

Figure 11: Collected representative samples

Size reduction process was conducted as described in Fig.8.

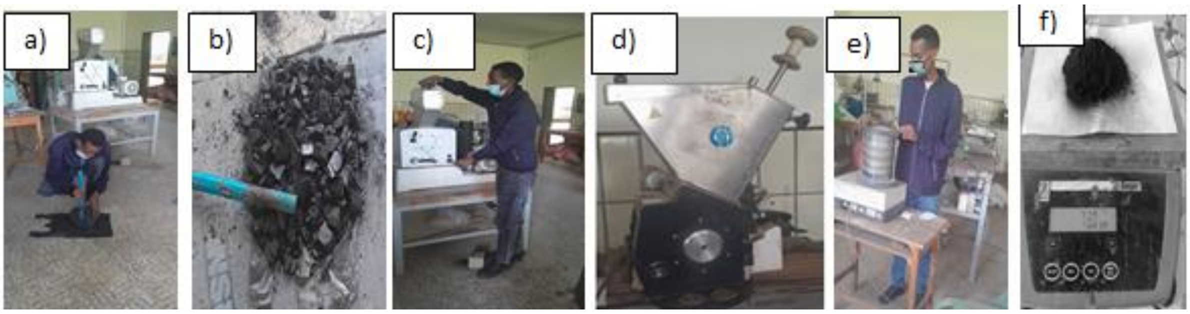

Figure 12: sample preparation for laboratory analysis a) manual reduction of massive coal size, b) crushed massive coal sample, c) size reduced in jaw crusher, d) crushing -500µm by hammer mill, e) separation of coal powder by different sieve size, and f) weighing coal powder

3.2.2. Experimental design

The following Fig. 9 provided a summary of all the samples experimental protocols used in this investigation.

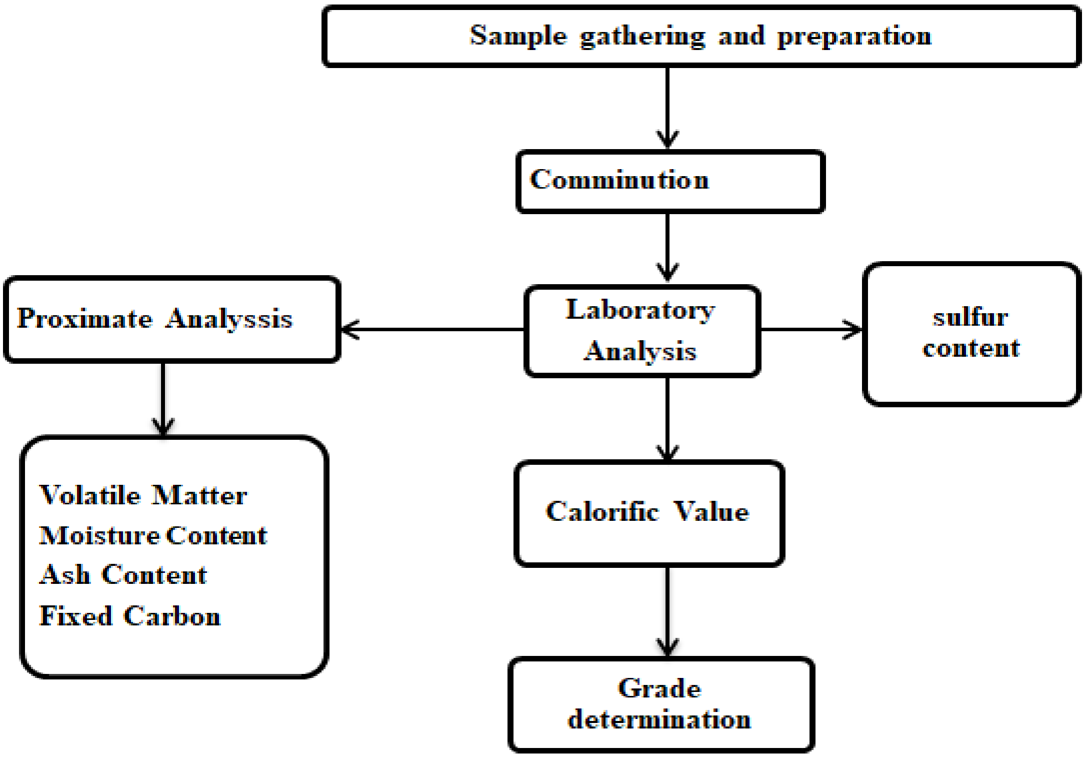

Figure 13: The overall experimental design for coal samples

3.2.3. Characterization of coal composition proximate analysis

This part involves measuring the moisture content (ASTM D3302), ash content (ASTM D-3174), volatile matter (ASTM D3175) and fixed carbon (ASTM D-388).

3.2.3.1. Moisture content determination

Moisture content is the weight loss of coal in a crucible, which is heated to about 105°C. A 1g amount of the -125μm fine-crushed coal sample is heated at 105°C (ASTM D3302) for about one hour in a silica crucible by using a Universal hot oven (Fig. 5E). The sample is then cooled in a desiccator and weighed. The crucible containing anhydrous coal is, heated and weighed, until the weight of the crucible, holding anhydrous coal becomes constant. The weight loss is expressed as the moisture content percentage.

$$\text{Moisture (\%)} = \frac{\text{wet weight} - \text{dry weigt}}{\text{wet weight}} x\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{equation (3.1)}$$

3.2.3.2. Volatile matter determination

The volatile matter is the weight loss of moisture-free coal at a given temperature and time. Place the 1g sample of moisture-free coal in a lidded silica crucible and heat it in the muffle furnace (Fig. 5E) for seven minutes to 925°±20°C (ASTM D3175). When taking it out, let it cool in the air, and then put it into the desiccators and measure once more. Weight loss is the unit of measurement of volatile matter.

$$\text{Volatile matter (\%)} = \frac{\text{loss in weight due to removal of volatile matter}}{\text{weight of coal sample used}} x\ 100 \ldots\text{equation (3.2)}$$

3.2.3.3. Ash content determination

A silica crucible, previously unfilled, was filled with 1g of finely powdered, -125µm air-dried coal sample that had been weighed. The crucibles were first heated to 800°C for nearly an hour to get free of any external particles. The crucible and sample were then put in a muffle furnace (shown in Fig. 5E) set at 750°C for almost half an hour. Then, the furnace temperature was raised to 850°C and heated at the said temperature for about one hour (ASTM D-3174). Finally, ash content calculation is determined by applying equation (3.3).

$$\text{Ash (\%)} = \frac{Z-X}{Y-X} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{equation (3.3)}$$

Where, X= weight of crucible in grams

Y= weight of coal + crucible in grams (before heating)

Z= weight of coal + crucible in grams (after heating)

3.2.3.4. Fixed carbon content analysis

The coal sample's percentage of fixed carbon was determined using ASTM D-388 guidelines. Next, fixed carbon was computed by deducting the total amount of ash, moisture, and volatile matter from 100 according to the following equation.

Fixed carbon content (%) = 100 - (%MC + %VM + %Ash)………………… equation (3.4)

3.2.4. Determination of sulfur content

The sulfur content in the coal sample was determined in the central laboratory of the Geological Survey of Ethiopia (GSE) by the Eschika method. Accordingly, 1g of the sample was mixed with 3g of Eschika mixture, which contained 2g of magnesium oxide and 1g of anhydrous sodium carbonate. One more gram of Eschka mixture was added to avoid the loss of sulfur as sulfur dioxide. The mixture was then subjected to a heat of 800℃ in a muffle furnace for 60 minutes. Thus, when the sulfur compounds, which were formed during the burning, were brought in contact with the Eschka mixture in the oxidizing environment, magnesium sulfate and sodium sulfate were formed. The digestion process of the product was performed by an acid, which was a 1M HCl solution and was stirred every so often for the combined time of 45 minutes. Following the filtration of the digested solution in 400 ml beakers, it was neutralized with three drops of methyl orange until the color was neutral. Consequently, the sample was boiling, and gradually added 10 ml of a 10% $BaCl_2$ solution over 30 minutes. After cooling completely with hot water, the solution was filtered, and the resulting $BaSO_4$ residue was burnt at 500 ℃ and weighed (Samaila et al., 2020).

The following chemical reaction formula summarized the sulfur content determination steps.

1. combustion process

Coal (containing sulfur compounds) + O_2 (from air) = CO_2 +H_2O +SO_2 +SO_3 + Ash

Sulfur oxides (SO_2 +SO_3) react with Eschka's mixture to form magnesium sulfate and sodium sulfate.

$SO_2 + MgO + O_2 \longrightarrow MgSO_4$

$SO_3 + Na_2CO_3 \rightarrow Na_2SO_4 + CO_2$

2. Extraction and acidification process

$MgSO_4(s) + HCl\ (aq) \rightarrow MgCl\ (aq) + H_2SO_4\ (aq)$

$Na_2SO_4(s) + HCl\ (aq) \rightarrow NaCl(aq) + H_2SO_4\ (aq)$

3. precipitation process

$BaCl_2\ (aq) + H_2SO_4\ (aq) \rightarrow BaSO_4(s) + 2HCl$

The sulfur concentration is determined using the produced $BaSO_4$ by applying equation (3.5)

Sulphur (%) = $\frac{32}{233}\, x\, \frac{weight\ of\ Barium\ sulfate\ formed(g)}{\text{weight of sample taken(g)}}\ x\ 100$ …………equation (3.5)

3.2.5. Calorific value determination

The calorific value was determined in the central laboratory of the Geological Survey of Ethiopia (GSE) by an adiabatic bomb calorimeter. Accordingly, one gram of powdered coal sample is weighed in a nickel crucible supported over the ring of the bomb, and then oxygen is puffed through the valve up to 25 to 30atm, which is enough for finishing combustion. The calorimeter with 2000mm of pure water was then filled with the bomb in its nickel bucket. The initial temperature was noted after the power was turned on, and the bomb was detonated once the bucket and bomb temperatures were equal. The bomb was withdrawn from the bucket, the maximum temperature of the reader, and then the knob valve was slowly opened to bleed off any residual gas pressure before attempting to unscrew the cap. The unburned fuse wire fragments were withdrawn from the bomb electrode, and, after straightening, the total length of wire was measured in centimeters to obtain the net amount of wire consumed. Finally, the bomb washing was titrated with a standard sodium carbonate solution using a methyl orange indicator.

Then the gross calorific value was calculated by applying Equation (3 6).

GCV = $\frac{\text{tW}-\text{e1}-\text{e2}-\text{e3}}{\text{m}}$ x 100 ……………………………………………equation (3.6)

GCV=Gross calorific value

t = temperature change

w = energy equivalent of calorimeter in cal/°c

e1 = adjustment in calories for the heat of nitric acid (HNO3) generation = (ml of standard alkali solution used in acid titration) if the acid titration was performed with 0.0709N alkali

e2 = adjustment in calories for the heat of formation of sulfuric acid (H2SO4

e3= adjustment in calories for the fuse wire's heat of combustion

m = mass of coal sample in gram

3.2.6. Fourier transforms infrared spectroscopy and X-Ray diffraction analysis

The FTIR and XRD analyses were conducted in Addis Ababa University’s Chemistry Department inorganic lab. For FTIR analysis, samples were measured on a Spectrum 65 FT-IR, Perkin Elmer, in the range of 4000~400cm^{-1} and with a resolution of 4cm^{-1}, while the XRD spectrum (2θ) range is (10°- 60°) and has a resolutions of 0.02°. The measured spectrum is the superposition of various spectral peaks, and it is difficult to get information directly. Therefore, this study uses the Origin Pro 2025 model software to solve the measured spectrum.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. Proximate analysis

Proximate analyses were conducted, according to the ASTM D3172 procedure for the determination of moisture, ash, volatile matter, and fixed carbon content. These factors help as major parameters at large when it comes to evaluating the quality of coal. Records on the coal's requirements and purity are presented in both table and graphical forms concerning proximate evaluation impacts.

4.1.1. Moisture content

The moisture content of coal within the study area ranged from 1.12% to 1.46% (by using equation 3.1). Table 4 indicates that Sample BT-5 represents the highest value of moisture content compared to the other samples, while the minimum value is represented in Sample BT-2. The largest moisture content indicates lesser carbon content, which results in reduced heating value and higher storage and transportation expenses (Wakuma & Assaba, 2017). Generally, higher moisture content in coal is an undesirable property, as it decreases the burning efficiency of the coal.

Table 4: Amount of moisture content obtained from experimental result

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Moisture Content (%)	1.19	1.12	1.37	1.16	1.46	1.26

4.1.2. Volatile matter

The volatile matter in the studied coal samples varies between 19.13% (BT-5) and 21.94% (BT-1), average 20.432% (by using equation 3.2). The volatile matter of coal samples in the studied area was lower in BT-5 and higher in BT-1 (Table 5). Different industries and power plants have their own requirements for volatile matter percentage during processing (Miroshnichenko et al., 2022). An acceptable level for volatile matter is 20-35% for metallurgical grade, min. 19% for thermal power plant and min. 24% for cement industry (Table 2). Accordingly, study area's coal volatile matter is found in the range of requirements for metallurgical grade industry and thermal power plant, while it is out of range for cement industry. This highlights the need for adoptive combustion technologies tailored to reduce volatile matter variability in coal from the studied region, ensuring optimal performance and emissions control in cement industry applications.

Table 5: Amount of volatile matter obtained from experimental analysis

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Volatile matter (%)	21.94	20.65	20.26	20.18	19.13	20.432

4.1.3. Ash content

The amount of ash produced from burning coal varies depending on the type of coal and its level of purity (Jovanovski et al., 2023). The ash content of the study area ranged from 33.99% in BT-1 to 48.57% in BT-5, with average 40.41% (by equation 3.3) as shown in (Table 6). Higher ash content reduces burning capacity, impacts combustion efficiency, raises handling costs, and results in significant slagging (Usman et al., 2022). Because high volumes of impurity diminish coal efficiency, the increase in ash content in coal causes a fall in quality or rank. BT-5 has values of ash content greater than another area, and therefore, has low quality or rank and vice versa with BT-1, which has the lowest ash content value. An adequate level for ash content should be less than 10% for metallurgical grade, 22-25% for Sponge iron plant, less than 34% for thermal power plant and 24-27% for cement industry (Miroshnichenko et al., 2022). Consequently, study area's coal ash content is found out of the range of requirements for all above mentioned industry. Therefore, multiple combustion strategies are required in order to effectively manage the variations of coal's ash content from studied area for appropriate industrial applications.

Table 6: Amount of ash content obtained from experimental result

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Ash content (%)	33.99	38.66	40.31	40.52	48.57	40.41

4.1.4. Fixed carbon

The fixed carbon provides a rough estimate of the coal's heating value (Anshariah et al., 2020). Table 7 shows that the studied coal samples have a fixed carbon content ranging from 30.84% to 42.88% (by using equation 3.4). All studied coal samples had less than 42.88% fixed carbon content, indicating that reduced carbon content has a significant impact on the coal's heating efficiency. From the studied area, BT-1 has the highest amount of fixed carbon; the coal sample from BT-5 has smaller levels of fixed carbon than other locations. The coal's volatile matter, ash, and moisture content are the cause of the decreased amount of fixed carbon. The location with the most fixed carbon (highest value) has a larger calorific value than the other location. Generally, the higher fixed carbon content results in an increase in heating value and decreasing ash content.

Table 7: Amount of Fixed carbon obtained from experimental result

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Fixed Carbon (%)	42.88	39.57	38.06	38.14	30.84	37.898

Generally, the results of proximate analysis obtained from laboratory experiments are indicated as a graphical representation shown in Fig.10.

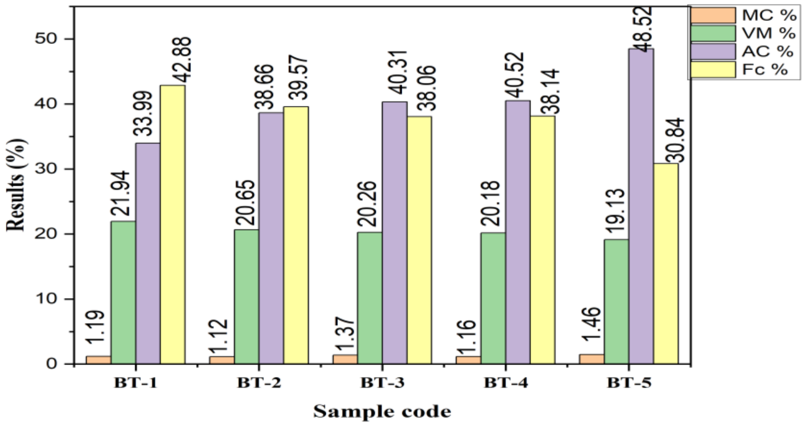

Figure 14: Graphical representation of proximate analysis for laboratory result

4.2. Fuel ratio

Fuel ratio is an analysis measure used in the examination of coal and other solid fuels; it is the ratio of fixed carbon to volatile matter. The fuel ratio is indicative of the combustion characteristics and the overall combustibility of the fuel (Samaila et al., 2020).

Table 8: Fuel ratio for studied coal sample

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Fuel Ratio	1.95	1.92	1.88	1.89	1.61	1.85

Due to its higher proportion of fixed carbon content and lower proportion of volatile matter, BT-1 coal possessed the highest fuel ratio (1.95), as indicated in Table 8. This indicated that it could be ignited more readily. On the other hand, BT-5 possesses the lowest fuel ratio (1.61), which is the least flammable. The best fuel ratio that had the highest value was good quality; hence, it burned longer and emitted fewer fumes.

4.3. Sulfur content determination

The investigated results of sulfur content were conducted by using the Eschka method in the central laboratory of the Geological Survey of Ethiopia, ranging from 0.17% to 0.21% (by using equation 3.5) and as shown in Table 9.

Table 9: Amount of total sulfur obtained from experimental result

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Sulfur content (%)	0.17	0.21	0.20	0.21	0.17	0.192

Based on the percentage of sulfur content, coals can be categorized into low-sulfur coal (< 1% Sulfur), medium-sulfur coal (1% ≥ sulfur < 3%), or high-sulfur coal (≥ 3% sulfur) (Chou, 2012a; Perez-Ruiz et al., 2019). The sulfur content obtained from this study area was confirmed within the standard range value that was from the value of lower sulfur content. This indicates that the sulfur content in these samples is relatively low, which positively affects their technological suitability.

4.4. Determination of calorific value

The Adiabatic Bomb calorimeter was used to determine the experimental value of calorific value for coal samples. According to Table 10, the calorific values of the studied coal sample range from 4114.7 Cal/gm to 5435.22 Cal/gm (by using equation 3.6). The results of the BT-1 and BT-2 calorific values are in accordance with ASTM standards that state coal quality greater than 5000 kcal/kg, and it is more used in the metallurgical and energy source industries (Ikwuagwu & Uzoegbu, 2017).

Table 10: Amount of calorific value obtained from experimental result

Sample code	BT-1	BT-2	BT-3	BT-4	BT-5	Average
Calorific value (Kcal/kg)	5435.22	5004.45	4904.26	4898.04	4114.74	4871.342
Calorific Value (Btu/lb	9,783.46	9,008.1	8,827.67	8,816.48	7,406.54	8,768.45

4.5. Coal ranking

Observing the result (Table 9) and based on ASTM D388-23 coal classification (Table 1), the gross calorific value (Btu/lb) of the coal sample BT-1 was 9783.46, which falls within the sub-bituminous coal ‘’A’’ rank, while coal samples BT-2, BT-3, BT-4 had calorific values of 9,008.01, 8827.67, and 8816.48, respectively, and they are classified within the sub-bituminous ‘’B’’ coal rank. In another way, coal sample BT-5 has a 7,406.54 Btu/lb calorific value and is classified as a sub-bituminous ‘’C’’ coal rank.

Generally, the gross calorific value (Btu/lb) is increased from 7406.54 to 9783.46, and this enables the ranking of the coal in the range of sub-bituminous C, sub-bituminous B, and sub-bituminous A according to world coal standards. The high volatile matter content in the result shown in Table 10 indicates the coal from the study area to be of low rank. This is because the content of the volatile matter decreases with an increase in coal rank (Ikwuagwu & Uzoegbu, 2017). The ash content of coals is counterproductive. The higher the ash content, the smaller the coal quality.

4.6. Comparisons with previous study

The classification of the coal resources will help in terms of their potential uses and optimizing use in energy production. Many studies were conducted in Ethiopia on the proximate analysis of coal deposits, which provided useful information on the general composition and combustibility of these deposits. In this project, proximate analysis results obtained for coal from the study area (Botor Tolay) are compared with those previously reported across different locations: Mush Valley, Yayu, Dowro, Kemashi, Witette and Gojeb-chida, respecting certain key parameters, namely, moisture content, volatile matter, fixed carbon, ash content, sulfur content, and calorific value. Such a comparison shows similarities and differences that lead to the conclusions of the viability of these coals in energy generation. Understanding these relationships not only adds to the knowledge base on Ethiopian coal but also helps in some strategic planning of the country's energy future.

Table 11: Some of previous studied coal categorization in Ethiopia

Previous studied coal in Ethiopia	**MC (%)**	**VM (%)**	**AC (%)**	**FC (%)**	**S (%)**	**CV (Kcal/kg)**	**REFERENCE**
Yayu	18.5	30.5	31.3	31.6	0.79	5136.5	Genetu & Kebede, 2024b
Witette	11	30.74	19.23	45.27	0.792	4448	Wakuma & Assaba, 2017
Dowro	10.67	30.34	33.73	25.26	0.67	3643.08	Minwuyelet, 2023
Mush valley	19.06	31.34	11.58	38.02	1.1	4117	Abraham, 2018a
Kemashi(Jeloleka)	1.97	27.78	33.62	41.63	0.55	5312.85	Haile, 2023
Kemashi(Michoka)	5.62	28.2	29.8	43.67	0.43	4989.4	Haile, 2023
Gojeb-Chida	18.74	39.37	38.96	61.02	0.43	5342	Genetu&Kebede, 2024b
Botor Tolay	1.26	20.432	40.4	37.898	0.192	4871.342	present study

MC - moisture content, VM - volatile matter, AC - ash content, FC - fixed carbon, CV – calorific value,
S – Sulfur content

4.6.1. Comparisons of moisture content with previous study

The moisture content is one of the critical parameters in the proximate examination of coal, as it greatly affects the calorific value and combustion efficiency of coal in general (Samaila et al., 2020; Ankur & Amarendira, 2022). This will help in understanding the suitability of these coals for energy production in Ethiopia. This comparison compares the results of moisture content obtained from coal sampled in Botor Tolay with findings reported in earlier studies of coals from regions such as Mush Valley, Yayu, Dowro, Kemashi, Witette, and Gojeb-chida. From the laboratory experiment analysis, the result showed that the average moisture content of the study area was 1.26%. The moisture content of Botor Tolay is lower compared to Mush Valley, Yayo, Dowro, Kemashi, and Gojeb-chida coal deposits (Fig. 15). Low moisture raises the overall energy content of coal, thereby making it more efficient in combustion and energy production. Burning is more efficient with better heat generated using less fuel during combustion. It is lighter and easier to transport, therefore reducing shipping costs. The industries that use coal for their processes, such as power generation and steel production, will find higher efficiency and better performance associated with coal that has lower moisture content.

Hence, the study area’s moisture content is more suitable for more efficient in energy production and reducing shipping costs than other previous studies mentioned above.

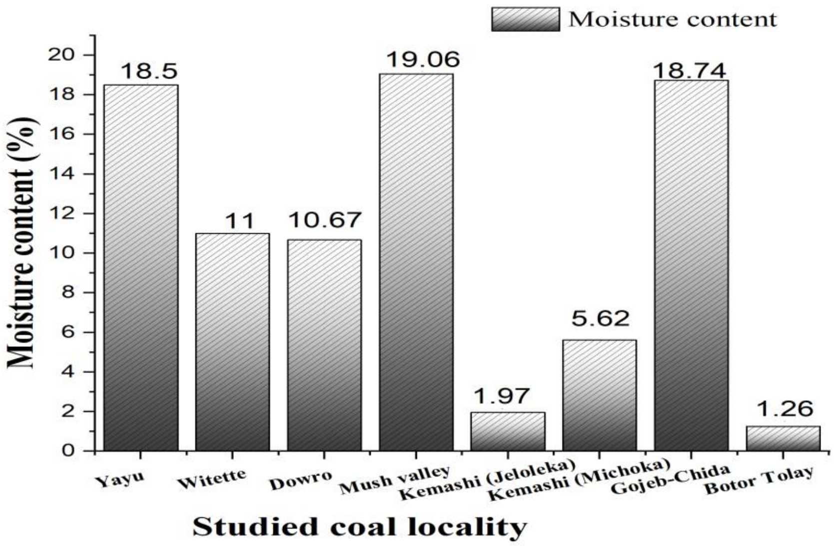

Figure 15: Comparison of Botor Tolay's coal moisture content with others locality

4.6.2. Comparisons of volatile matter with previous study

The volatile matter in the proximate analysis is a very crucial component of coal, mainly influential in determining combustion characteristics and energy efficiency (Ankur & Amarendira, 2022). In Ethiopia, the variability in volatile matter among different coal deposits has great implications for energy production and utilization. This comparison compares the volatile matter content obtained from the proximate study of coal samples from Botor Tolay with findings from previous studies conducted in regions such as Mush Valley, Yayu, Dowro, Kemashi, and Gojeb-chida. The result obtained from the laboratory experiment analysis showed the average volatile matter of the study area to be 20.432%. Comparing with localities that have been studied previously, it shows the lowest volatile matter content (Fig. 16). Coals with low volatile matter usually have a higher fixed carbon content that leads to increased calorific value and energy output on combustion and are usually steadier in burning and thus suitable for applications requiring consistent and reliable heat generation. Fuels with low volatile matter content produce less smoke and gaseous emissions. It means better air quality and following ecological regulations. In general, the lower the volatile matter is, the better the quality of coal.

Hence, the study area's low volatile matter produce less smoke and gaseous emissions and steadier in burning and thus more suitable for applications requiring consistent and reliable heat generation than other previous studies mentioned above.

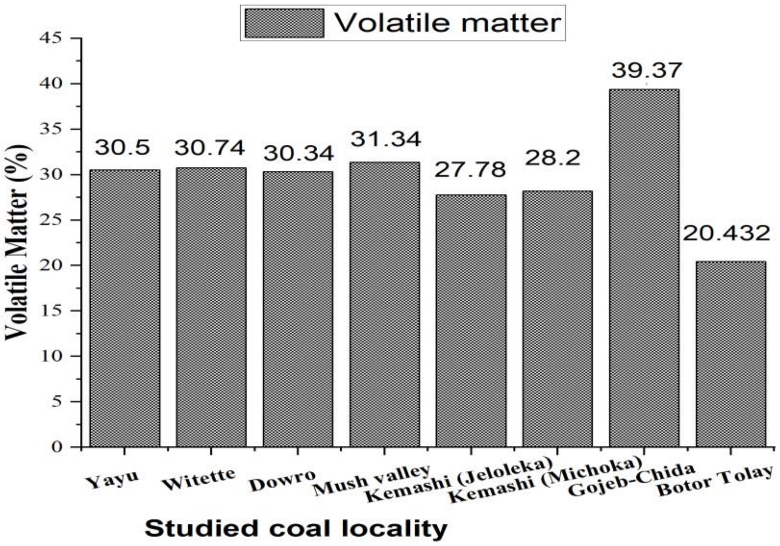

Figure 16: comparison of Botor Tolay's coal volatile matter with others locality

4.6.3. Comparisons of ash content with previous study

Ash content in coal is a vital factor in its proximate analysis and influences the quality of coal combustion (Rao & Anuradha, 2019), environmental impact (Khoyutanov & Gavrilov, 2018), and suitability for different applications. In addition, regions of Ethiopia have highly variable ash contents arising due to a response to the different geological formations and types of coal that exist. This research is focused on comparing the results of ash content obtained from the proximate analysis of the coal samples with previous studies conducted in Mush Valley, Yayo, Dowro, Kemashi, and Gojeb-chida. The result obtained from the laboratory experiment showed that the average ash content of the study area was 40.4%. Compared to previously studied localities, the result indicates the studied area has the highest value of ash content (Fig. 17). The quantity of coal ash content required for the cement industry, metallurgical grade, sponge iron plant, and thermal power plant are 24–27%, <10%, 22–25%, and <34% respectively (Meshram et al., 2015).

Therefore, different combustion technologies are needed to effectively manage the high variations in coal ash from the studied area for appropriate application.

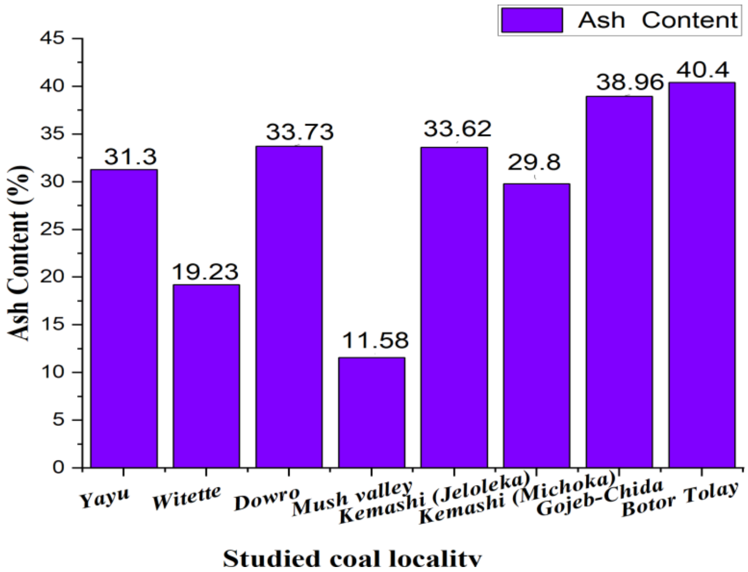

Figure 17: Comparison of Botor Tolay's coal ash content with others locality

4.6.4. Comparisons of fixed carbon with previous study

One of the proximate analysis indicators for coal is fixed carbon, which has high correlations between concentrations and the fuel energy content as well as the combustion heat. With an increase in the percentage of fixed carbon, the calorific value of the coal will increase. This explains that coal calorific value is highly associated with fixed carbon concentration (Imran et al., 2019). As a result, different fixed carbon locations in Ethiopian coal seams will limit their potential for use in industry and energy production.

According to the result of the laboratory test, the average ash content of the study area was 37.898%. The study reveals that the study area has a greater percentage of fixed carbon than Yayu and Dowro but less than Kemashi, Gojeb-chida, Mush valley, and Wittete areas in comparison to coal localities previously researched (Fig. 18). Increased fixed carbon content results in more burnable carbon content, which means lower waste and increased efficiency of energy generation. Coals with higher fixed carbon tend to burn longer, making them suitable for applications requiring sustained heat. Generally, higher fixed carbon content means coal of a high quality.

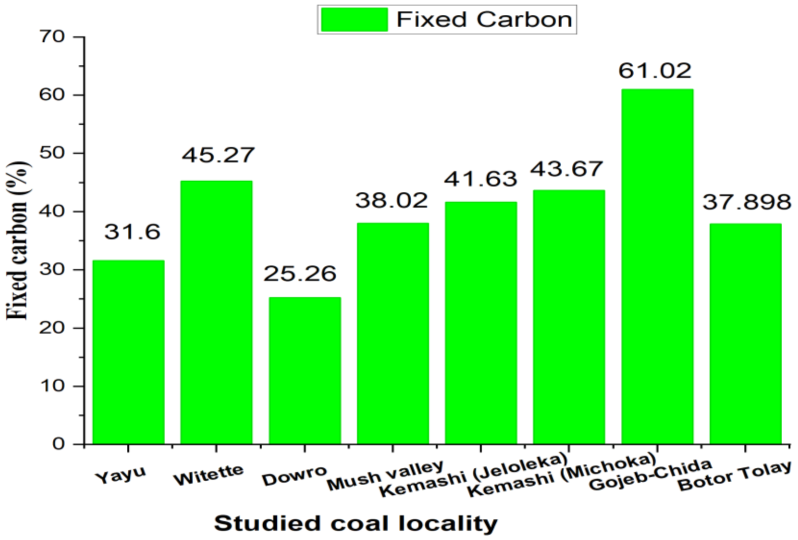

Figure 18: Comparison of Botor Tolay's coal fixed carbon content with others locality

4.6.5. Comparisons of sulfur content with previous study

Sulfur in coal is of prime importance concerning both combustion efficiency and environmental impacts associated with sulfur dioxide (Samaila et al., 2020). This research deals with the sulfur content obtained through proximate analysis of coal sampling at Botor Tolay in comparison to other investigations in the Mush Valley, Yayo, Dowro, Kemashi, and Gojeb-chida regions. The result obtained from the laboratory experiment showed the mean sulfur content of the study area was 0.192%. The sulfur content of Botor Tolay is lower compared to Mush Valley, Yayo, Dowro, Kemashi, and Gojeb-Chida coal deposits (Fig. 19). Lower sulfur levels increase its marketability because of cleaner energy production (Kudełko, 2003). Other industries, such as those related to metallurgy and cement, also prefer low-sulfur coal due to its cleaner-burning characteristics, which could ensure better quality products. Lower sulfur coals, as a rule, produce less ash (Samaila et al., 2020), hence less disturbance with waste management treatment and disposal processes.

Therefore, the sulfur content obtained from this study area was lower than all previously studied areas mentioned above and (<1% S), the result is in agreement with (Chou, 2012b) which is states that within the low-sulfur coal standard.

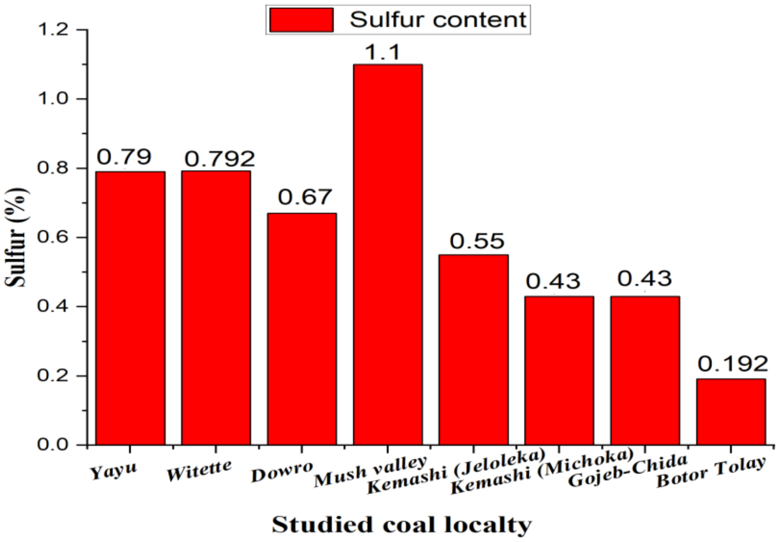

Figure 19: Comparison of Botor Tolay's coal sulfur content with others locality

4.6.6. Comparisons of calorific value with previous study

The calorific value is the amount of energy that coal contains in it. It is a property of coal, which depends upon its chemical constituents and moisture content. The value of fuel primarily depends on the GCV of fuel (Xiu-xiang et al., 2009b; Ankur & Amarendira, 2022). The main purpose of this comparison is to compare the calorific values obtained in previous research from areas like those of Mush Valley, Yayu, Dowro, Kemashi, and Gojeb-chilga with those received from proximate analysis of Botor Tolay coal samples. The analysis from the laboratory experiment revealed that the average calorific value of the study area was 4871.342%. Botor Tolay coal possesses a higher calorific value than Mush Valley, Dowro, and Wittete, but the calorific value of the surveyed area is lower than that of Gojeb-Chida, Yayu, and Kemashi areas (Fig. 20). Higher calorific value means that less coal is required to produce the same quantity of energy, leading to more efficient energy generation and typically resulting in more complete combustion, minimizing unburned carbon and ash production, which can simplify waste management.

Therefore, coal from the Botor Tolay deposit has a higher heating value than coal deposits found in the Mush valley, Dowro and Wittete areas.

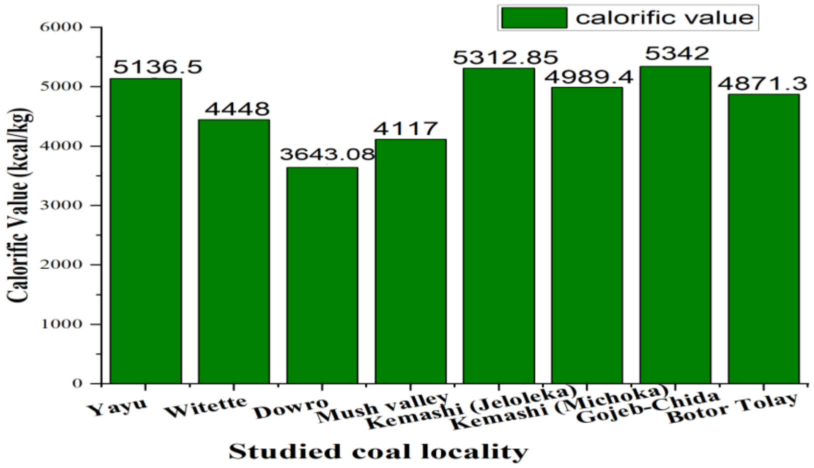

Figure 20: Comparison of Botor Tolay's coal calorific value with others locality

4.7. Proximate analysis and coal quality

The result obtained from proximate analyses of the studied coal sample is given in Figure 10. The average moisture and ash contents of the studied coal samples were 1.26 % and 40.4%, respectively. The averages of moisture and ash content for Yayu, Wittete, Dowro, Mush Valley, Kemashi Jeloleka, Kemashi Michoka, and Gojeb-Chida are given as 18.5%, 31.3%, 11%, 19.23%, 10.67%, 33.73%, 19.06%, 11.58%, 1.97%, 33.62%, 5.62%, 29.8%, and 18.74%, 38.96%, respectively (Table 11). As the depositional setting, freshwater swamp coals would typically be wetter than brackish or marine-setting coals depending on the mixed preservation of the organic matter (https://en.wikipedia.org/wiki/Coal_analysis). The average value of moisture content of the studied coal sample is significantly lower compared to all the above-studied domestic coal. The studied coal's low moisture (1.26%) suggests arid depositional conditions compared to Yayu, Wittete, Dowro, Mush Valley, Kemashi Jeloleka, Kemashi Michoka, and Gojeb-Chida. The moisture content required by the cement industry is less than 8% (Meshram et al., 2015). Therefore, values recorded in the coal samples are generally found in the range of requirements specified for the cement industry.

However, when compared to the ash content of the coal being studied, the ash content of the previously studied domestic coals is quite low. Ash content reflects inorganic material (e.g., clays, sulfides) added during peat deposition or later groundwater intrusion. Coals deposited near a current source of sediment (e.g., river deltas) are more likely to be ash and tectonic post-formational movement can introduce minerals via hydrothermal fluids or volcanic ash, adding ash content (Nystrand et al., 2021). The studied coal's high ash (40.4%) indicates significant mineral contamination, possibly from siliciclastic influx during formation, contrasting with Yayu, Wittete, Dowro, Mush Valley, Kemashi Jeloleka, Kemashi Michoka, and Gojeb-Chida coal deposits. Similarly, low ash content improves the coking quality; it is a condition for coals to be used in coke manufacturing. The ash content should be less than 10% for good coking quality (Diez et al., 2002; Akpabio et al., 2008). According to industry observations, raising the ash content of coke by 1 weight percentage decreases the production of metal by 2 or 3 weight percentages. Therefore, the coal used in this study does not have good coking qualities due to the presence of a higher amount of ash content and the need for ash reduction technology for the sake of using it properly. The volatile matter in the coal sample used in this study is well below Yayu coal, which has 30.5%, Wittete coal, which contains 30.74%, Dowro coal with 30.34%, Mush valley coal, which contains 11.58%, Kemashi Jeloleka coal, which contains 27.78%, Kemashi Michoka, which contains 28.2%, and Gojeb-Chida coal, with 39.37% (Table 11). Volatile matter is not a part of coal; it usually evolves as tar during carbonization. The alteration from lignite to anthracite involves an increase in fixed carbon and progressive loss of volatile matter due to geological processes such as deep burial and tectonic metamorphism.

(Levine, 1993). High-volatile bituminous coal, with high volatile matter, creates high pressure during carbonization and is thus injurious to the coke oven (Akpabio et al., 2008). The percentage of medium-volatile bituminous coal is around 22% to 31% as shown in Table 1. Thus, Yayu coal, Wittete coal, Dowro coal, and Kemashi coal fall into the medium-volatile bituminous coal category. Whereas, the low-volatile bituminous coals contain about 14% to 22% of volatile matter content. ASTM D388-23 presented in Table 1 suggests that Botor Tolay coal is of low volatile bituminous rank.

The analyzed coal samples, as shown in Table 11, reveal that the Gojeb-Chida sample has the highest fixed carbon content at 61.02%. Following closely is the Wittete sample with 45.27% fixed carbon, and the Kemashi (Michoka) sample with 43.67% fixed carbon. Lower levels of fixed carbon were found in the Kemashi (Jeloleka) (41.63%), Mush Valley (38.02%), Botor Tolay (37.898%), Yayu (31.6%), and Dowro (25.26%) coal samples. The fixed carbon content is the carbon remaining in the material after volatile materials have been driven off. It has been commonly used as an approximation of the coke yield from a coal sample (Akpabio et al., 2008; Diez et al., 2002). This suggests that the Botor Tolay sample with the lowest value has less carbon for coke formation, followed by Yayu and then Dowro.

Botor Tolay coal has the lowest sulfur content of 0.192%. The highest sulfur content of 1.1% is observed in the mush valley sample. In the carbonization process, sulfur is undesirable because most of it would be retained in the coke. An acceptable level for sulfur content is 0.6% of the metallurgical grade, 0.8% for thermal power plants and 0.6% for the cement industry(Meshram et al., 2015). Therefore, the sulfur content of Botor Tolay coal is within the required range of Metallurgical grade, thermal power plant, and cement industry.

4.8. Major element analysis

X-ray fluorescence analysis, in general, provides a way to determine element contents in almost every kind of natural material and thus is also conventionally employed to analyses the quality of coal and coal ashes (Willis et al., 2014; Revenko & Pashkova, 2024). Accordingly, Table 10 allows consideration that the types of elements in coal samples of the minerals were major silicon (Si), aluminum (Al), iron (Fe), niobium (Nb) and titanium (Ti). Their average contents are 73.2%, 14.842%, 3.6082%, 2.91% and 1.79%, respectively.

Table 12: Elemental composition of studied coal samples obtained from XRF analysis

Sample code	Major element (unit: %)				Trace element (unit :%)										
	Si	Al	Fe	Ti	Nb	Sn	Cd	Mo	Cu	Zr	Zn	Pb	Sb	Pd	Bi
BT-1	75.7	16.27	3.07	1.65	1.14	0.04	0.14	0.44	0.08	0.95	0.10	0.05	0.04	0.09	0.06
BT-2	79.93	11.83	3.66	1.17	1.00	0.04	0.13	0.41	0.09	0.74	0.09	0.06	0.04	0.08	0.05
BT-3	73.17	17.14	3.80	2.38	1.12	0.04	0.16	0.44	0.10	1.08	0.24	0.05	0.06	0.09	0.08
BT-4	69.18	15.14	3.85	1.99	1.16	0.04	0.15	0.34	0.10	1.09	0.25	0.06	0.05	0.08	0.08
BT-5	67.9	13.83	3.66	1.78	0.99	0.04	0.13	0.42	0.10	0.74	0.10	0.06	0.06	0.08	0.06
Avg	73.2	14.84	3.61	1.79	2.91	0.04	0.14	0.41	0.09	0.92	0.16	0.06	0.05	0.08	0.07

Chemical elements in coal are part of organic and inorganic compounds. XRF study is used for the quantitative determination of the elemental coal composition present in the sample.

Table 13: Chemical compositions of coal samples obtained from XRF analysis (wt. %)

Sample code	Chemical composition					
	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)	Nb_2O_5 (%)	others
BT-1	67.37	25.53	3.65	1.15	1.36	0.945
BT-2	73.38	19.17	4.49	0.84	1.23	0.892
BT-3	64.66	26.74	4.49	1.64	1.33	1.142
BT-4	65.60	25.34	4.88	1.47	1.47	1.235
BT-5	67.33	24.19	4.85	1.38	1.31	0.935
Average	67.668	24.194	4.472	1.296	1.34	1.0298

Table 13 shows that the XRF analysis of the coal sample contains the maximum amount of SiO_2 (67.668% by wt.) and Al_2O_3 (24.194% by wt.), followed by Fe_2O_3 (4.472% by wt.), and TiO_2 (1.296% by wt.). The presence of SnO_2, SnO_2, ZrO_2, PbO, MoO_3 and CdO, Bi_2O_3 was found in a small amount. These findings are in good agreement with the results of the XRD analysis mentioned under the section on XRD analysis. The uses of coal in industry, most notably the production of electricity, metallurgy, and construction materials, depend on the availability of SiO_2, AlO_3, FeO_3, and TiO_2 (Hutabarat et al., 2021).

Energy Generation: Increased SiO_2 and AlO_3 content will translate into increased ash content, reduced calorific value of coal and thermal power station combustion process efficiency. Cleaning processes should be regular in order to ensure process efficiency due to the fact that oxides lead to boiler fouling and slagging (Ameh, 2019). Due to reactivity with sulfide substances, FeO_3 in ash represents a likely increased risk of boiler system corrosion. Although its low concentration will have a lesser contribution, an equitable concentration of TiO_2 will increase the slag fluidity under combustion operation conditions (Hutabarat et al., 2021).

Construction and Metallurgy: SiO_2 and Al_2O_3 lead to a higher volume of slag in the blast furnace process for steelmaking, which increases the production cost. Al_2O_3 also aids the fluidity and melting of slag under controlled conditions and is hence employed in efforts to optimize running conditions in blast furnaces (Liu et al., 2018). A balanced amount of Fe_2O_3 is desirable in the recovery of iron from metallurgical processes. High silica and alumina content will be advantageous in the sense that they would be utilized as raw material to manufacture clinker for cement manufacturing, whereas the appearance of TiO_2 in trace amounts would have a weak effect on the material's properties (Ameh, 2019). Such a type of oxide-bearing coal is generally applicable where high refractory character is required or for supplementary cement material in cement manufacturing.

Therefore, to ensure efficiency, minimize downtime, and prolong boiler life in coal-fired power plants, facilities must pursue aggressive ash management practices such as advanced monitoring of ash chemistry, optimal combustion conditions, and periodic mechanical or chemical cleaning of deposits. Additionally, firing coals with favorable Si/Al ratios and low reactive oxides could decrease operating costs and environmental impact.

4.9. Functional group analysis

The FTIR method is a non-destructive method for characterizing qualitative and semi-quantitative studies of functional groups in coal and can also be used for the characterization of insoluble organic compounds in coal (Ahmad et al., 2022). Thus it is a means of estimating the comprehensive absorbance of organic components based on the main functional groups, such as alkyl CH, CH_2, and CH_3, aromatics C=C and C-H, carbonyl/carboxylic acids C=O, and hydroxyl-OH.

From the coal under study, FTIR analysis was made to understand the functional groups, that exist on the surface of the coal samples. Figure 21 shows the absorption peaks of functional groups of five studied coal samples.

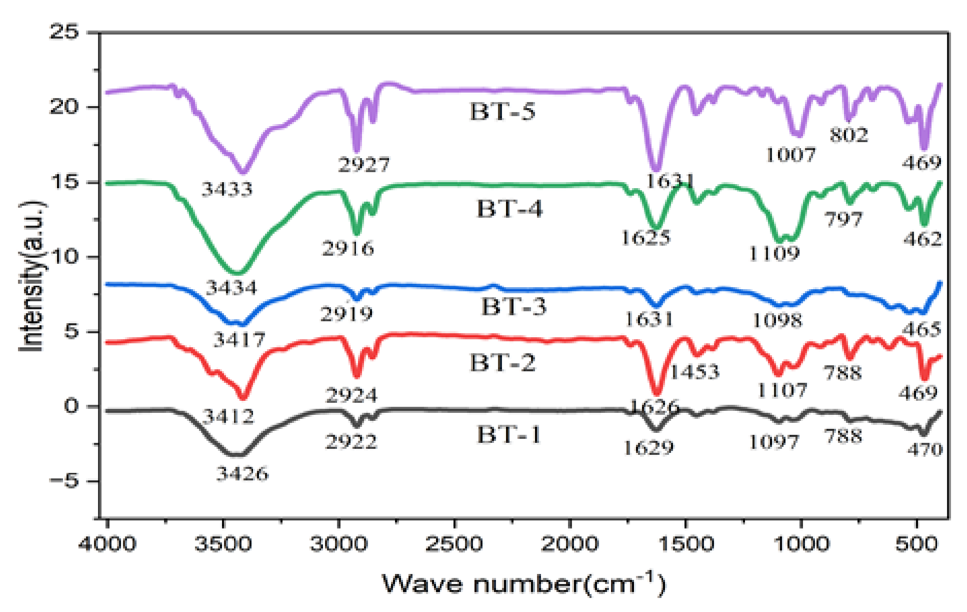

Figure 21: FT-IR spectra of studied coal sample

The absorption bands are present within two wave number regions of 3426–2919 cm^{-1} and 1631−400 cm^{-1}. Additionally, it was found that the distribution of functional group absorption bands was comparatively similar among the five coal samples. The absorption pattern from many scholars was used, attributing to the bands (Saikia et al., 2007; Tanykova et al., 2021; Y. Zhang et al., 2021; X. Zhang et al., 2023) and identification of the absorption peaks in each wave number compared to conventional patterns to the bands shown in Table 14.

Table 14: The characteristic of FTIR coal surface functional groups

Wave numbers ranges	Functional groups	Compound class
850-550	C-Cl stretching	Halo compounds(s)
840-790	C=C bending	Alkene(m)
920-885	O-H bend	Carboxylic acids(m)
1060-1020	Si-O-Si or si-O-C stretching	Sulfoxide (s)
1200-1070	C-O stretch	Ethers
1480-1450	C-H bending	Alkane(m)
1605-1595	C=C stretching vibration	The aromatic hydrocarbon of the benzene ring (m)
1620-1610	C=C stretching	α, β unsaturated ketone(s)
2935-2915	C-H stretching	Alkane(m)
3600-3200	O-H stretching	Alcohol, water

Where s-strong and m-medium

The coal samples examined contain oxygen functional groups such as -OH and C=O, and aromatic functional groups such as C=C and C-H. The absorption bands ranging from 3434-3426cm^{-1} are caused by the -O-H stretching of the alcohol and water groups in the coal samples. A broad band of absorption ranging from 3433-3412 cm^{-1} is caused by the N-H and

O-H groups. In addition, peaks between 2922-2929 cm^{-1} show the C-H stretching of alkanes, while peaks between 1625-1631 cm^{-1} indicate aromatic C=C stretching of alkene groups, and peaks at 1096 cm-1 are caused by the C-O stretch of the ether group in some coal samples.

The peaks at 2922 cm^{-1}, 2924 cm^{-1}, 2929 cm^{-1}, 2916 and 2917cm^{-1} appear to indicate the presence of C-H stretching of alkanes in BT-1, BT-2, BT-3, BT-4, and Bt-5 coal samples respectively. The peaks at 1629 cm^{-1}, 1626 cm^{-1}, 1631 cm^{-1}, 1625 cm^{-1} and 1631 cm^{-1} are observed due to aromatic C=C stretch of alkenes group in BT-1, BT-2, BT-3, BT-4, and BT-5 coal samples, respectively. The peaks at 1452 cm^{-1} correspond to the alkanes group in BT-2 and the peaks at 1096cm^{-1} in BT-3 correspond to C-O stretch of the ether group. Most of the bands in FTIR spectra of coal between 1100 and 400 cm^{-1} are due to clay minerals such as quartz, kaolinite, and illite (Saikia et al., 2007a). In the coal under investigation, the representative peaks at 1098 cm^{-1}, 788 cm^{-1}, 469 cm^{-1}, 790 cm^{-1}, 469 cm^{-1}, 1096 cm^{-1}, 528 cm^{-1}, 471 cm^{-1}, 797 cm^{-1}, 462 cm^{-1} in BT-4, 1007 cm^{-1}, 802 cm^{-1}, and 469 cm^{-1} are attributed to these mineral groups.

Overall, coal functional groups can be used to give an idea to the operators about what quality coal can be stored, and blending can be done with different grades of coal to achieve the specifications.

The peaks of the O-H stretching vibration of low-rank coal are at 3400 cm^{-1} (Dai et al., 2023). Hence, the coal sample analyzed is classified as low-rank coal based on the -OH stretching oscillation peaks. Blending with higher-rank coal is necessary for optimal utilization and efficient energy production.

The hydroxyl groups can have a great influence on the moisture content of the coal (Y. Zhang et al., 2021), and it is necessary to control storage conditions so as not to allow high moisture retention and the possibility of self-combustion. In the studied coal sample, the presence of -OH stretching vibrations was detected, which indicates moisture content and clay minerals. For storage strategy, it is critical to control moisture content, so maintaining low moisture content is recommended to prevent hydrolysis of aliphatic groups and -COOH formation as described by (Gao et al., 2023) and prevent penetration of water by using covered storage or drainage facilities.

Clay minerals like illite and kaolinite expand upon water absorption, leading to water content gain and swelling coal piles, which facilitate quick degradation of the coal (Yan et al., 2024). These accelerate oxidation, self-heating, and the generation of fine particles during storage and handling. Dust release and environmental hazard are promoted by these minerals (Chryss, 2017). Prevention of the detrimental effects of clay minerals on coal storage is encouraged through dust control practices such as chemical sealants or water sprays, compacting of the stockpile to limit porosity and air permeation, and sealing agents or covered storage for prevention of water uptake.

Aliphatic hydrocarbons signal the end of reactive aliphatic chains. They are prone to oxidation in that they form peroxides (-C–O–O-) that initiate fires (Zhang et al., 2021). Therefore, in order to reduce exposure to air when coal is stored, seal stockpiles with polymer emulsions to reduce oxygen inflow and dust emission and store coal in flat layers to reduce air pockets, which prevent low-temperature oxidation.

The generation of volatile organic compounds (VOCs), specifically phenols and ethers, is linked to oxygenated functionalities such as C-O-C, -OH, and carbonyls (Balachandran, 2014). Such functionalities provide the potential for air pollution and reactivity. They are accountable for low vapor pressure and quick formation of molecules through generating autoxidation mechanisms (Cao et al., 2024; Rissanen, 2021). In secondary organic aerosol formation, this triggers the development of highly oxygenated organic molecules, tends to produce more than one oxygen atom to yield highly oxygenated organic molecules (HOMs). Although carbonyl compounds are a signature of ozone formation potential (OFP) in an urban atmosphere, ethers (C-O-C) and phenolic (OH) groups are also responsible for ozone formation potential (OFP) (Cao et al., 2024). Control of oxygenated VOC emissions, especially phenols and ethers, is an efficient method of controlling secondary pollution. Oxygenated volatile organic compound (VOC) measurement enables the reactive organic carbon pools in urban and industrial regions to be monitored. In general, oxygenated groups are the main drivers of ozone and aerosol formation; therefore, targeted emission control needs to be adopted in order to prevent secondary pollution.

4.10. Crystal chemistry structure analysis

The mineral compositions of the coal samples are examined by using X-ray diffraction (XRD) (Fig. 22). Kaolinite ($Al_2Si_2O_5[OH]_4$) (JCPDS 29-1488) peaks are found at $2\theta^o$=10.2°, 12.55°, 39.9°. Quartz (SiO_2) (JCPDS card no. 46-1045) peaks are found at $2\theta^o$=20.88°, 25.4°, 26.6°, 39.5°, 42.41°, 50.2°, 54.92° (Pfeiffer et al., 2021). Pyrite (Fe_2S) peaks are found at $2\theta^o$ = 36.4°, 39.88°, 47°(JCPS card no. 042–1340 Iron Sulphide (Pyrite)). Whereas, Anatase (TiO_2) peaks are found at $2\theta^o$ = 24. 8° , 37.3° and 55.1^o (JCPDS card no. 00-0016. 021-1272 Titanium oxides (Anatase, syn)(Li et al., 2014).

Thus, the XRD results obtained from the studied coal sample contain minerals of quartz, kaolinite, pyrite, and Anatase. The presence of quartz (SiO2), Anatase (TiO_2) and pyrite (Fe2S) in the coal sample analyzed in this work is usually revealed and responsible for ash increase, as confirmed by (Chen et al., 2017a). Quartz indicates the silica content, which affects the coal's physical properties and reactivity. The presence of quartz in coal can seriously harm power plants, boiler tubes, and coal handling equipment, which will impair the facility’s ability to operate (Bandopadhyay, 2010). High quartz content in coal lead to increased wear on equipment during processing.

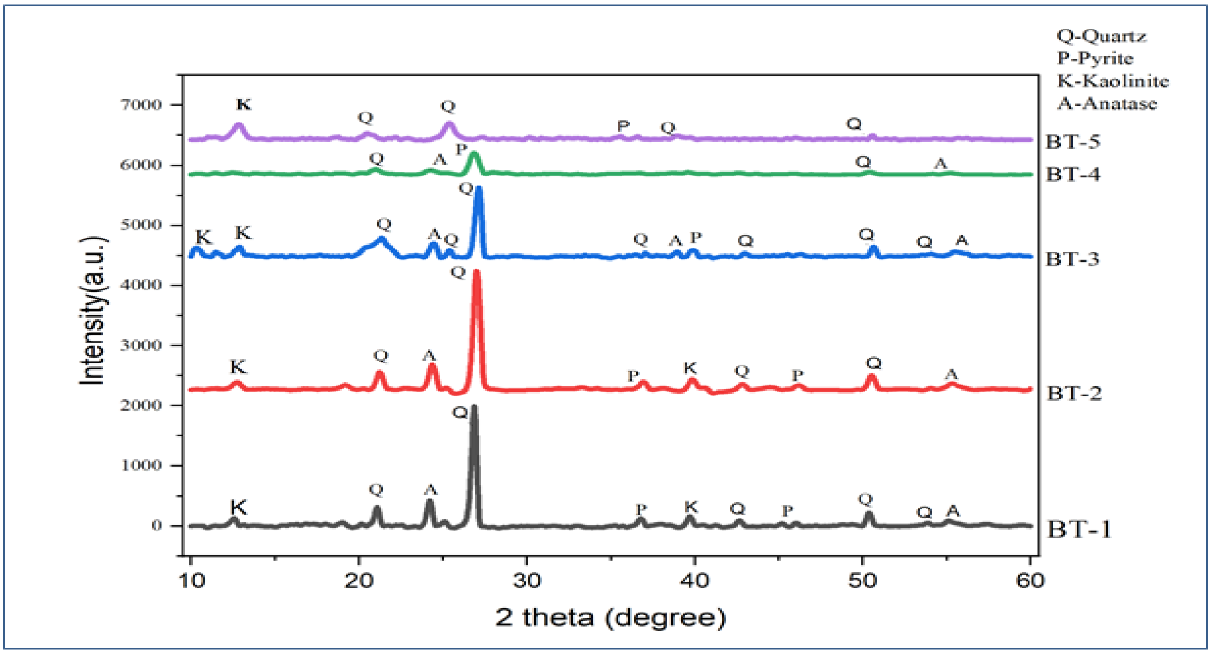

Figure 22: XRD spectra of coal sample

Since the sulfur influences the emission of pollutants and combustion efficiency, the presence of pyrite would imply that the sulfur would also be present. Sulfuric acid is produced when pyrite (FeS_2) is oxidized naturally or artificially in the presence of water, according to (Mahanta et al., 2020). Kaolinite is one of the major constituents of coal ash. Its presence may result in high total ash content, and it may impact the fuel efficiency and heat value.

Generally, the XRD result verifies the existence of quartz (SiO_2), pyrite (Fe_2S), and anatase (TiO2), the cause of ash increase in the coal under investigation, prevalent, and the obtained results agree with (Chen et al., 2017b; Jiang et al., 2021; Saikia et al., 2007b)

CHAPTER FIVE

5. CONCLUSSIONS AND RECOMMENDATIONS

5.1. Conclusions

The study area (Botor-Tolay) coal deposit is covered with diverse rock types that have the potential for depositional environment information. Dominantly, Tertiary volcanic and coal-bearing sedimentary rocks underlie the study area. This study focused on a number of methods to classify the composition of coal and assess its consequences for coal quality indicators. The result of proximate analysis of the five coal samples shows that coal from BT-2 has the lowest percentage of moisture content (1.12%), while that of BT-5 has the highest percentage of moisture content (1.46%). Moisture in coal is an undesirable property as it decreases the burning efficiency of the coal. In the case of ash content, coal from BT-5 has the highest percentage of ash content (48.52%), and BT-1 has the lowest percentage of ash content (33.99%). Ash is also undesirable as it reduces combustion.

The coal from BT-1 was found to have a higher fixed carbon percentage, thus making it the most combustible, followed by the coal from BT-2, BT-3, BT-4, and lastly, coal from BT-5. The coal from BT-1 had the highest percentage of volatile matter (21.94%) and is expected to burn more evenly with smoky flames, followed by BT-2 (20.65%) and lastly, BT-5, which has the lowest percentage (19.13%). The grades of coal in the study area were identified to fall under sub-bituminous ‘’C’’ coal groups to sub-bituminous ‘’A’’ coal groups based on coal classification by rank (ASTM D388-23). Calorific values of the studied area ranged from 7406.54 Btu/lb in BT-1 to 9783.46 Btu/lb in BT-5, and the average sulfur content of coal samples was 0.192%. From FTIR analysis, -OH stretching vibrations were detected, which indicates moisture content and clay minerals. Also, phenols and ethers were observed, which are responsible for volatile organic compound (VOCs) generation. The XRF analysis of the coal sample revealed that it has a high percentage of SiO2 (67.668% by wt.), Al2O3 (24.194% by wt.), Fe2O3 (4.472% by wt.), and TiO2 (1.296% by wt.). In addition, the XRD analysis found silicon, kaolinite, and pyrite in the studied coal samples, which are responsible for the ash increase. Therefore, results obtained from both XRF and XRD analysis are in agreement with the presence of high ash content (average 40.4 %), which was obtained from laboratory analysis results. Generally, the finding indicates that proximate analysis revealed significant variations in fixed carbon and ash content, while sulfur and moisture content analysis indicated a correlation with coal quality and had the low value in percentage.

However, this study was limited by sample size and geographic focus, indicating a need for broader studies to validate these findings. Future research could explore what the implications are for coal composition on both combustion efficiency and environmental impact in various geographic regions. The research underlines the critical role of coal composition in determining quality indicators and lays the foundation for future studies in the search for optimization of coal utilization.

5.2. Recommendations

- The proximate analysis laboratory results indicate that the coal in question has high ash content and a low percentage of fixed carbon. This suggests that the coal contains more impurities or inorganic components. As a result, it is recommended that the beneficiaries of this coal use the flotation technique to improve its quality.
- As it offers complete analysis, improved accuracy, and standardization, and allows informed decision-making for various applications, the full ultimate package for coal analysis is recommended for accurate and effective coal categorization.

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Annex

Laboratory result

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

Customer Name :- Likasa Bakala

Sample type:- Coal Powder

Sample Preparation:- 60 Mesh

Date Submitted:-12/12/2024

Issue Date:- 30/12/2024

Request No:-GLD/RN/687/24

Report No:- GLD/TR/4215/24

Number of Sample: Five(05)

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
BT-1	1.19	21.94	42.88	33.99	5435.22	0.17	100gm
BT-2	1.12	20.65	39.57	38.66	5004.45	0.21	100gm
BT-3	1.37	20.26	38.06	40.31	4904.26	0.20	100gm
BT-4	1.16	20.18	38.14	40.52	4898.04	0.21	100gm
BT-5	1.46	19.13	30.84	48.57	4114.74	0.17	100gm

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

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Geochemical Laboratory Desk

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