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The Development of Process Flow Sheet for Froth Flotation Method of Coal Deposit in The Case of Yayo Area, South-Western Ethiopia

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Abstract

Coal is a mixture of organic and inorganic materials and has the ability to burn easily. The objective of this research was to develop a froth flotation flow sheet for the Yayo coal deposit using METSIM simulation software. In this study, the flotation flow sheet for the Yayo coal deposit was created by conducting proximate analysis value and ultimate analysis value. The particle sizes examined were 500µm, 250µm, 125µm, and 63 µm. Based on the particle size distribution, it was found that the 125µm particle size was most suitable for producing high- quality coal with a high percentage yield, as determined by the METSIM simulation software. The proximate analysis values obtained through the simulation software indicated that the moisture content of the coal was 21.25%, the volatile matter content was 22.3%, and the ash content was 6.42%. The average values of the ultimate analysis revealed that the coal contained 62.022% carbon, 4.558% hydrogen, 27.1653% oxygen, and 12.87% sulfur, as determined by the METSIM software simulation. Moreover, the carbon content result obtained from the METSIM simulation software was 79.49%, indicating that the coal in the study area is classified as bituminous coal, which is known for its relatively high carbon content.

Keywords: Froth Flotation, Proximate Analysis, Ultimate Analysis, Particle Size

Introduction

Coal is a sedimentary rock that exhibits physical and chemical heterogeneity. It is primarily composed of organic material, namely carbon, along with minor amounts of inorganic elements such as hydrogen, oxygen, sulfur, and nitrogen [1]. In Ethiopia, coal is found in various regions, but it is generally characterized by low calorific value, high sulfur content, and high ash content [2]. To overcome these limitations and enhance the usability of low-grade coal, several technologies have been employed, including physical, chemical, and physicochemical beneficiation methods [3].

Physicochemical beneficiation, in particular, has emerged as a widely used and crucial approach in modern coal beneficiation technology. This method exploits the differences in hydrophobicity between coal particles and mineral matter to effectively separate finely dispersed minerals and eliminate inert components [4]. Among the physicochemical processes, froth flotation stands out as one of the most efficient and cost-effective techniques for coal beneficiation. It relies on the surface wetting properties of fine coal and the selective attachment of hydrophobic oil reagents to separate impurities from pure coal [5].

Due to the growing industrial zones and increasing living standards in Ethiopia, there is a significant energy demand that cannot be met by the existing supply. The poor quality and low calorific value of local coal have compelled industries such as cement, metallurgical steel, and textiles to rely on imported coal, primarily from South Africa, at a considerable cost in foreign exchange [6]. To address this issue, upgrade the locally available coal using physicochemical beneficiation techniques and develop a flotation flow sheet specific to the Yayo coal deposits is very crucial.

Material and Methods

The coal sample was simulated using the METSIM simulation software, which allowed for the creation of flow sheets. The flow sheet consisted of various common unit operation symbols, such as a stockpile, a screen, a jaw crusher, and conveyors. The coal was broken through gravity impact and discharged through plates, resulting in particle sizes of approximately 500μm, 250μm, 125μm, and 63μm. Once the coal reached the desired size, it was screened into fractions of -500μm and +63μm.

The flotation cell separators, typically of the deep bath Type, received the materials ranging from -500μm to +63μm separately. The floats were transferred from the primary separator to the secondary unit, which generated medium and high-grade coals. The rejected hard shale was removed, and the middling was retreated in the Baum Jig Section. Spraying screens were used to filter the separator products before flotation machines were employed to remove the fine coal from the effluent. This flotation stage was essential to prevent the fine coal from disrupting the specific gravity range of the natural media and causing a significant circulation load of coal particles.

The media used in the main flotation section, with a regulated density and size of (+125, -500 mesh), was a percentage of the tailings. The +125 portion from both the Bradford Breakers and the clean coal was processed using Baum Jigs. The resulting clean coal was screened into different size categories, and additional dewatering was carried out using wedge bar screens and a centrifuge. The product was then pumped to large diameter settling cones for treatment in the froth flotation section, along with the underflow from the 63μm wedge bar screen. The waste shale from the secondary Bradford Breaker was combined with the waste from the Baum Jigs and utilized as filler. The supply for the centrifuge was obtained from the settling cones and fed into the flotation section. Reagents, including a combination of cresylic acid-creosote serving as a collector and frother, were added at this stage. The separation process was achieved using flotation machines equipped with four-bladed froth paddles.

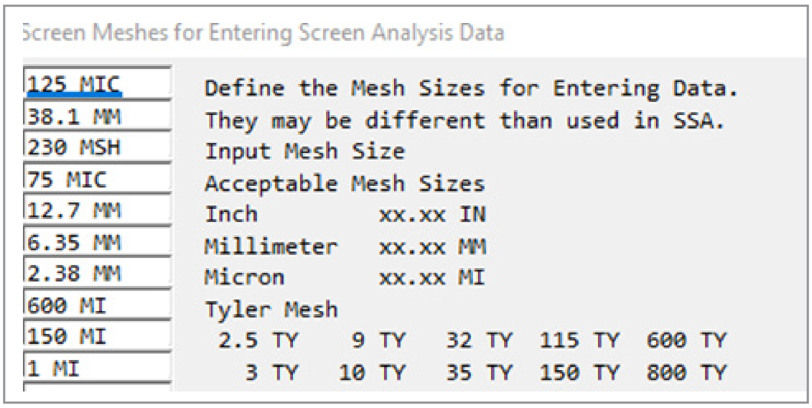

Figure 1: Screen Data Impute of 125 μm

The METSIM simulation software was utilized to select screen size distributions, equipment dimensions, and other crucial process models. The software also facilitated the establishment of the flow sheet and determination of the types of equipment required. Using plant data, specific operations were simulated by the models, which allowed for the prediction of circuit performance. The models were capable of updating coal data and presenting the results in the form of annotated flow sheets, tables, and graphs on the screen or in printed reports.

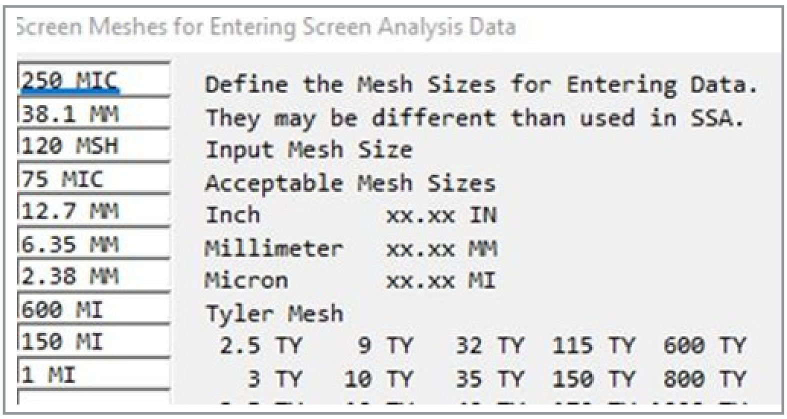

Figure 2: The Screen Inputs for the 250 μm METSIM Simulation Software.

During the flotation process, several characteristics such as particle size, feed rate, and reagent addition needed to be fine-tuned. In this study, the working parameters were optimized based on the theory of one variable at a time. The highest efficiency in mineral removal was considered as the response variable, and key parameters included feed rate, collector dosage, frother dosage, and particle size. Through the optimization process, these parameters were adjusted to achieve the desired performance and improve the efficiency of the flotation system.

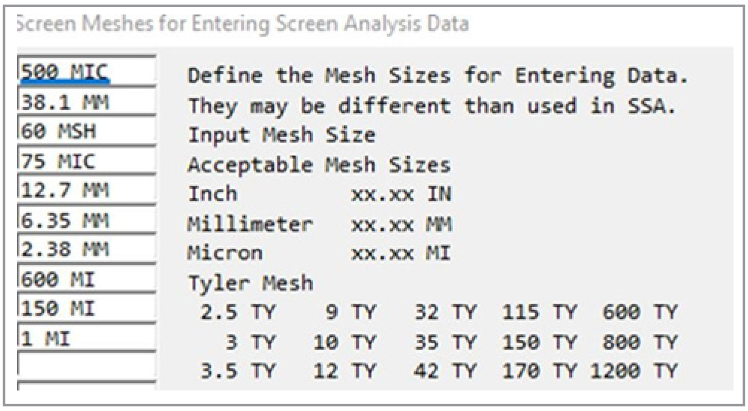

Figure 3: The Screen Information Inputs for the 500 µm in METSIM Simulation Software

Coal Size Reduction

The flow sheet incorporates three treatment steps for different size ranges. This includes using Baum Jigs for the -250, +125 µm fraction, Dense Medium for the -500, +250 µm fraction, and froth flotation for the -125, +63 µm fraction. The -125, +63 µm fraction was specifically chosen for high-quality coal cleaning. In addition to recovering low-ash coal fines, flotation played a crucial role in preparing coal flotation tailings for use as separation media in dense media, as well as improving the disposal of fine waste or tailings.

Circuit Design and Simulation

Using the METSIM simulation software, the flow sheet for the froth flotation process was developed and circuit configurations were simulated.

Ultimate Analysis

The METSIM simulation software's modeling program calculated the mass fraction percentages of key elements in the coal, such as carbon, hydrogen, sulfur, nitrogen, and frequently, oxygen by difference. The results of the ultimate analysis, combined with the coal's calorific value, were used to perform combustion calculations, including estimating coal feed rates, calorific value, and sulfur emissions.

Proximate Analysis

The METSIM simulation software was employed to conduct proximate analysis, which involves determining the moisture content, volatile matter (VM), ash, and fixed carbon in a coal sample. The software automatically displayed the results based on the provided data input. Proximate analysis is a fundamental and widely used method for coal assessment, forming the basis for many coal procurement and performance prediction indices used by utility operators. The software also determined the total moisture content of the coal sample by simulating the flotation process using a 600 g coal sample. Various measurements were obtained for the raw coal moisture content. Standard sieves were used to screen the concentrate and tailings at a 500 µm (60 meshes) size according to the METSIM simulation data.

Results and Discussion

Comminution Circuit Design

The comminution circuit was designed using Agg flow software, with target liberation sizes of - 500, 250, 125, and 63 microns.

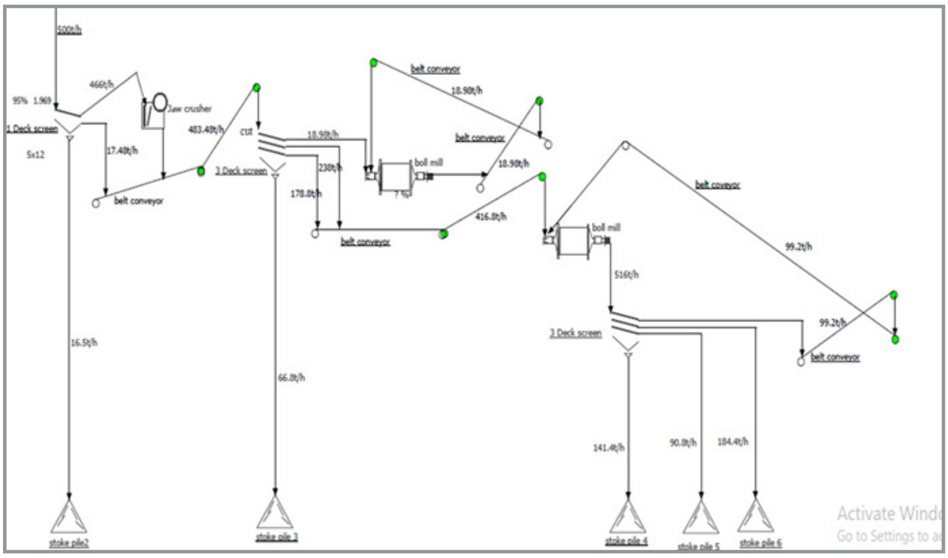

Figure 4: Coal Comminution Flow Sheet Created by Agg Flow Software

Circuit Design and Simulation
The jaw crusher was used to reduce the feed with a top particle size of 500 µm to 125 µm. The crushed product was then subjected to flotation at a 125 screen aperture to separate it into -250 µm and +125 µm streams. This separation was necessary because the Yayo coal predominantly consisted of medium-quality coal particles in the +125 µm fraction, as observed in previous studies and confirmed in this study. In the first process option, flotation was employed to purify the -250 µm and +125 µm fractions, which had higher levels of ash and sulfur. These fractions were subsequently discharged into the tailings.

In the second flow sheet (Fig.6), a classifying cyclone was added to the first process option to further separate the -125 µm stream into -125 µm and +63 µm fractions. The second and third process alternatives were chosen for handling the -125 + 63 µm fraction, utilizing a spiral and a concentrating table, respectively. Since coal accounted for only 3.13% of the total feed mass and exhibited a weak flotation response, the -63 µm coal stream was directly discarded into the tailings without undergoing further processing.

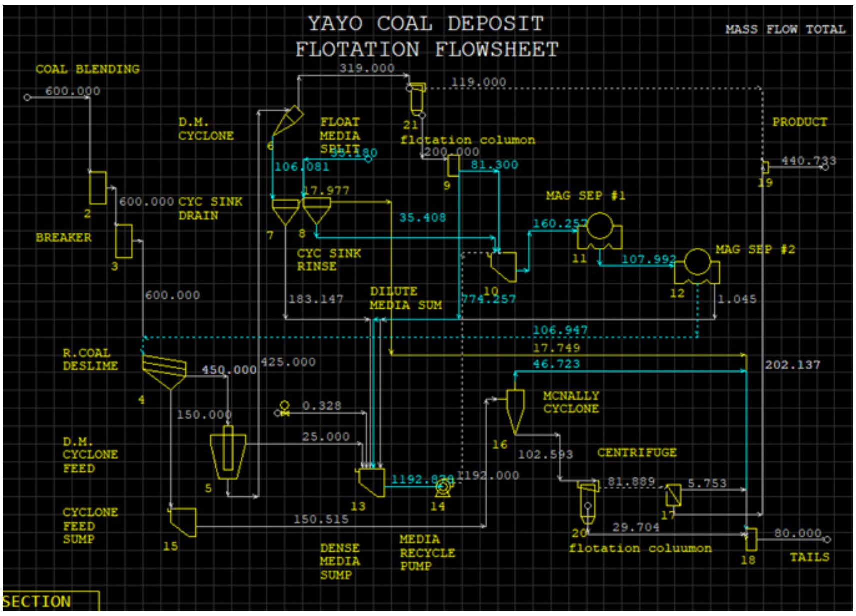

Figure 5: METSIM Simulation Software Flow Sheet at 500 µm

During the simulations, the screen sizes of the concentrating devices were adjusted within their realistic ranges of -500 µm to +63 µm for froth flotation. All the models were conducted with a plant capacity of 600 t/h, which was chosen for the purpose of comparability and based on the current rates of coal production in different coal zones within the Yayo coal field. The simulations provided information on the yield, ash content, and sulfur content of the clean coal product, as well as the characteristics of the plant tailings.

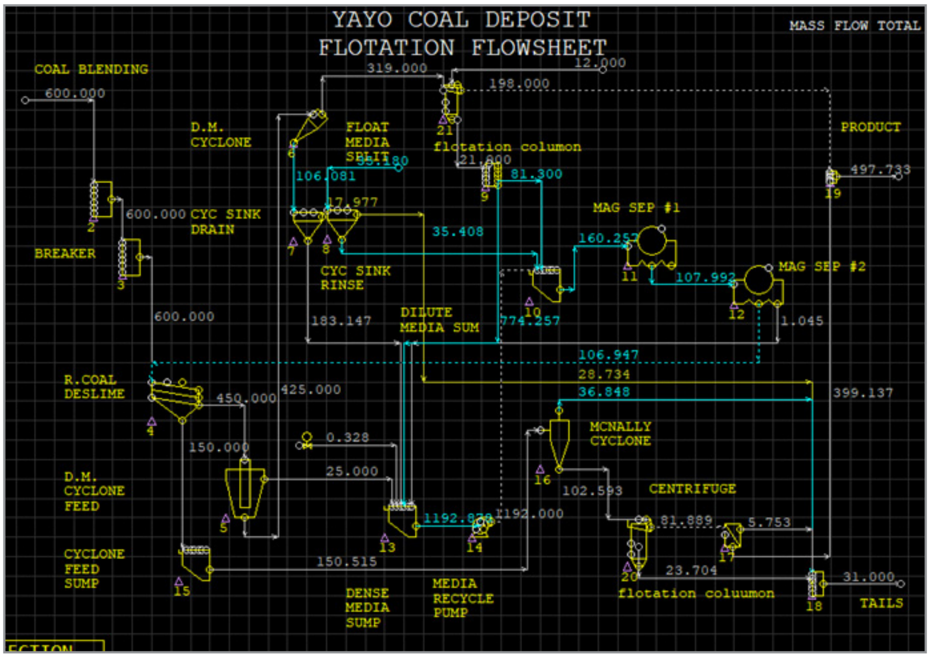

Figure 6: METSIM Simulation Software Flow Sheet at 250 µm

Table 1: Percent Compositions of Ash, Carbon and Sulfur at 250 µm

Component	Wt. Frac.	Mol. Frac.	ST/HR
cCOAL	0.6364700	0.8884083	4.7833378
cASH	0.3218850	0.0898163	2.4191
cSUL	0.0416449	0.0217752	0.3129791

The analysis of the coal size distribution at 250 µm revealed a production of 497 t/h of cleaned coal product and 31 t/h of tailings. The dominant size fraction of the coal was found to be 63.64% by weight, with a yield of 32.19% ash content and 4.16% sulfur content. The presence of a high proportion of micro-fine particles in the coal poses challenges for flotation, as it increases the likelihood of attachment of high-ash particles to the coal surface. This can negatively impact the efficiency of the flotation process.

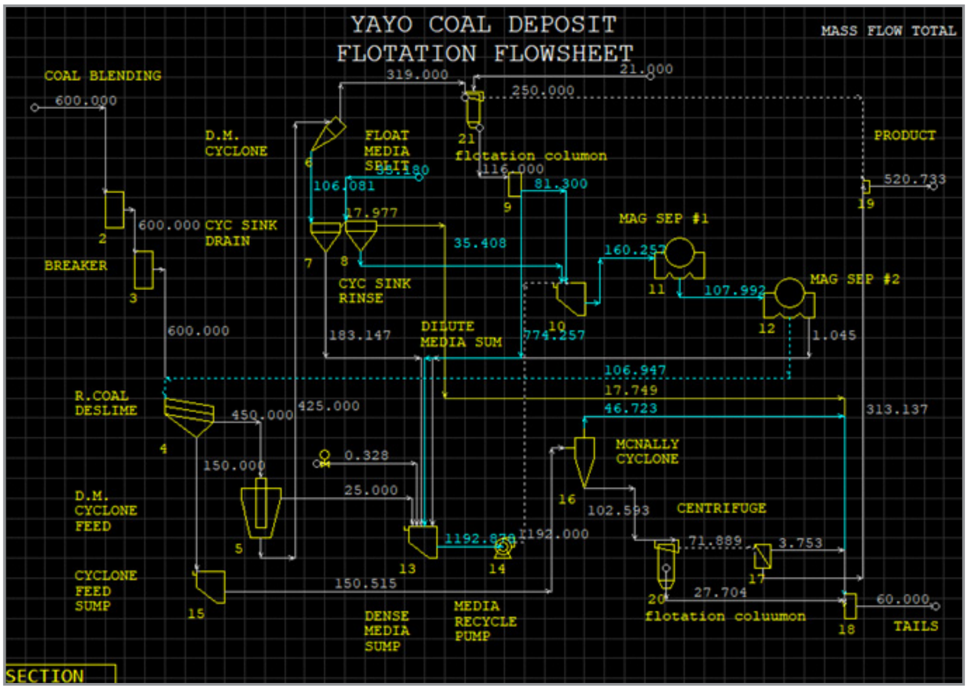

Figure 7: METSIM Simulation Software Flow Sheet at 125 µm

Table 2: Percent Compositions of Ash, Carbon and Sulfur at 125 Screen Size

Component	Wt. Frac.	Mol. Frac.	ST/HR
cCOAL	0.7947556	0.9424144	158.95113
cASH	0.1621182	0.0384291	32.423654
cSUL	0.043126	0.0191564	8.6252182

Based on the analysis conducted using the METSIM software, the Yayo coal samples from southwest Ethiopia exhibited the following characteristics: the ash content, clean value, and sulfur content were determined to be 77.62%, 17.76%, and 4.6%, respectively. The calorific value of the Yayo coal sample was also found to be 77.62%. These results indicate that employing the froth flotation process to enhance the calorific value of the specified sites is a suitable strategy. The Yayo coal contains high levels of impurities and ash, which impede its efficient combustion. However, it has a high calorific value and releases a significant amount of heat.

The METSIM simulation software was utilized to determine the sulfur content of the cleaned concentrate coal sample, which was found to be 520 t/h. Among the different screen sizes tested (500 µm, 250 µm, and 125 µm), the 125 µm screen size yielded the highest sulfur content. The high sulfur content in the coal contributes to the development of highly sulfuric ash, which reduces the heating capacity of the burned coal. Form the METSIM simulation observed that, the product increases from 497 t/h to 520 t/h as the particle size decrease from 500 microns to 125 microns (fig.5-7).

Proximate Analysis

Determination of Moisture Content

In terms of proximate analysis, the moisture content of the coal samples was determined. Moisture is present in the coal as fluid matter, including gas and gas-liquid inclusions associated with both organic and inorganic components .Higher-rank coals generally have lower moisture content, while lower-rank coals tend to contain more physically and chemically adsorbed water [7]. The moisture content of the Yayo coal samples ranged from 15% to 21.02%, with an average value of 17.19%. Among the different sample sizes, the 500 µm sample had the highest moisture content, while the 63 µm sample had the lowest.

The high moisture content in Yayo coal can reduce its combustion efficiency and prolong the evaporation process. The 500 µm sample, due to the presence of combustible material, had higher moisture content, leading to lower heat content per kilogram of coal and increased heat loss from evaporation and vapor superheating. On the other hand, the 63 µm sample had relatively lower moisture content, which has less impact on the coal's heat content. To ensure effective storage and utilization of coal, optimal moisture content is required, as too little moisture makes coal heavier to transport, decreases its calorific value, and makes it more challenging to handle.

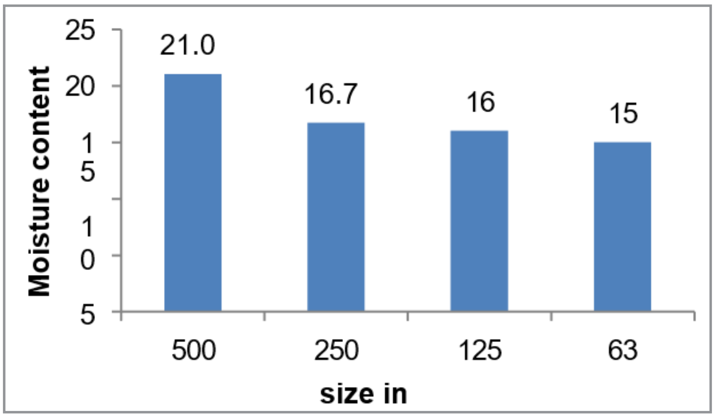

Figure 8: Moisture content vs size

Determination of Volatile Matter

When coal is subjected to high temperatures, it undergoes thermal decomposition, resulting in the release of volatile matter [8]. These volatilities include combustible gases like steam and vapor, as well as incombustible gases like carbon monoxide and hydrocarbons. The analysis indicates that the highest concentration of volatile matter is observed in coal particles with larger sizes. As the particle size decreases, the amount of volatile matter decreases as well (as shown in Figure 10). Additionally, as the amounts of combustible gases increase, the amount of fixed carbon decreases, leading to a decline in the heating value of the coal.

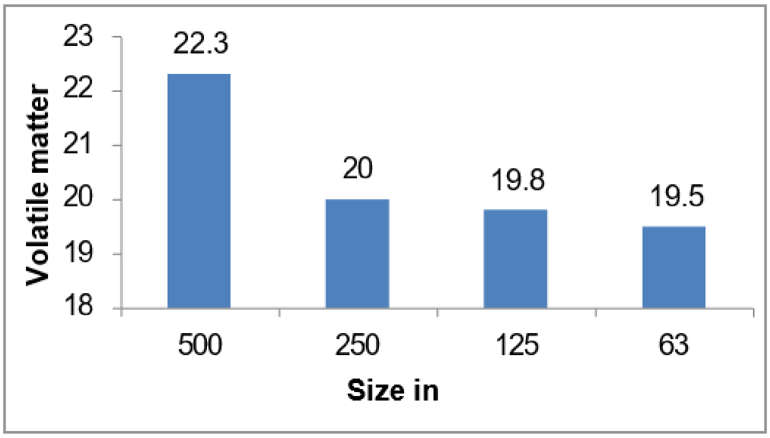

Figure 9: Volatile matter vs Particle size

Measurement of Ash Content
The ash concentration of the analyzed coal samples was determined using the METSIM modeling software. The average ash concentration values varied widely across different sample sizes, ranging from 3.2% to 24.5%, with an average value of 11.58%. It is worth noting that except for samples 500 and 250, the results showed a considerable range, indicating that the majority of the coal sample had high ash content. An increase in ash content can have several negative effects, including reduced burning capacity, higher handling costs, decreased combustion efficiency, and significant slagging [9].

The management system for coal ash during the coal utilization process depends on the quantity of ash produced and its behavior at high temperatures. At elevated temperatures, coal ash tends to become sticky and eventually melts into molten slag. As the ash content of coal increases, the quality or rank of the coal decreases due to the presence of more impurities, which lowers the efficiency of the coal [10]. On the other hand, when the ash content decreases, there is either a smaller amount of unburned material or a reduced presence of impurities such as rock and dirt. It is also worth mentioning that as the ash content rises, the volatility of the coal decreases, and vice versa. Moreover, an increase in moisture content can lead to an increase in coal volatility.

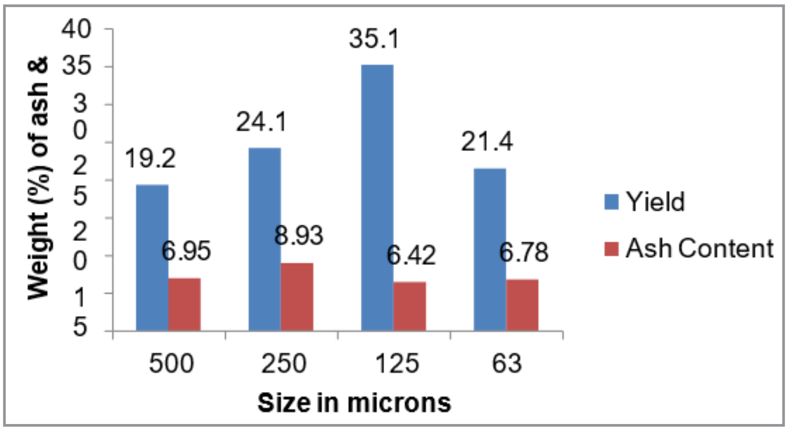

Figure 10: Yield and Ash Content vs Particle Size Distribution

The results indicate that the sample sizes 500 and 250 have relatively high amounts of ash content, suggesting the presence of unburned materials (as shown in Figure 11). These sample sizes are likely to have lower carbon contents and provide less heat energy. On the other hand, sample sizes 250 and 125 have lower amounts of ash content, indicating that the coal has a moderately high level of purity. In general, the particle size of 125 microns yielded a high percent yield, indicating low ash content and high carbon content.

Fixed Carbon Amount
The fixed carbon content of coal is commonly used to estimate its heating value. It is generally observed that as the rank of coal increases, the fixed carbon content also increases [11]. According to the analysis, the coal sample exhibits high fixed carbon content at the 125-micron particle size, indicating a potentially higher quality for coal in this size range. The 500-micron particle size, on the other hand, has high percentage values of moisture content, volatile matter, and ash content. Below is Table 3, displaying the proximate analysis results of the coal obtained through the METSIM simulation software:

Table 3: METSIM Simulation Software Proximate Analysis Result of Coal

Size in (µm)	Moisture (%)	Volatile matter (%)	Ash (%)	Fixed carbon (%)
500	21.02	31.13	16.10	38.02
250	16.75	25	16.08	63.65
125	16	23.8	16.01	79.47
63	15	22.5	15	35
Average	17.19	25.6	19.87	54

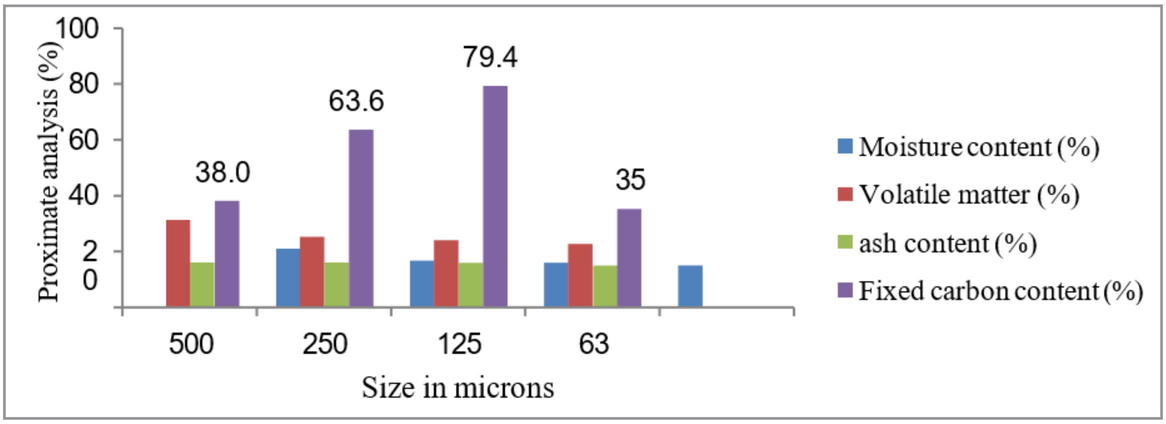

Figure 11: METSIM Simulation Software Proximate Analysis Result of Coal

The particle sizes of 125 and 250 microns yielded the highest fixed carbon content, with the 125- micron size showing a higher value compared to the 250-micron size. This indicates that the coal sample could potentially be floated more effectively at the 125-micron particle size (as shown in Figure 12).

Ultimate Analysis

Moving on to the ultimate analysis, the mass fraction percentages of the main components of coal, including nitrogen, carbon, hydrogen, sulfur, and oxygen, were determined. The ultimate analysis provides crucial information for combustion-related analysis, such as determining the required air for burning, sulfur emissions, and the composition of combustion gases [12].

Table 4: METSIM Simulation Software Ultimate Analysis Result of Coal

Stream	Carbon (%)	Hydrogen (%)	Oxygen (%)	Sulfur (%)
Washed coal	62.022	4.558	27.1653	12.87
Tailing	6.077	10.18	53.33	1.86

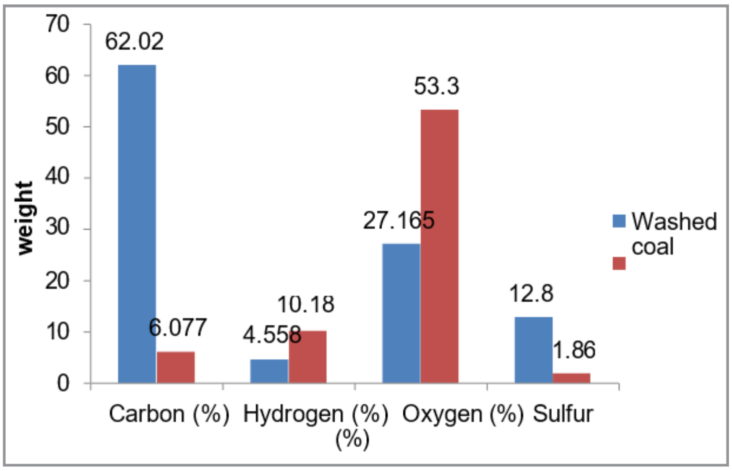

Figure 12: Yayo Coal Sample's Average Ultimate Analysis Value

Figure 13 illustrates the average ultimate analysis values of Yayo coal. Based on these values, it can be determined that the sulfur content in this coal is relatively low compared to other components such as carbon, hydrogen, oxygen, and sulfur. The higher carbon content indicates a cleaner coal with higher quality.

Conclusions

In conclusion, the physicochemical and thermal characterization of Yayo coals in southwestern Ethiopia was performed, and the carbon, nitrogen, oxygen, sulfur, and hydrogen contents were determined and compared. Proximate and ultimate analysis was conducted on four different sample sizes from the Yayo coal area. The analysis revealed that the coal samples had a significant carbon content and relatively low sulfur and ash percentages.

The simulated coal samples from the study exhibited moisture contents ranging from 16.5% to 21.2%, volatile matter values between 19.5% and 22.3%, and ash content ranging from 6.42% to 89.3% as determined by proximate analysis. The ultimate analysis showed average values of 62.022% carbon, 4.558% hydrogen, 27.1653% oxygen, and 12.87% sulfur for the coal.

The size analysis of the Yayo coal through sieve testing using screen sizes of 500 μm, 250 μm, and 125 μm resulted in cleaned coal products with yields of 59.51%, 63.65%, and 79.47%, respectively. Due to a significant volume of coarse coal particles, the conventional sieves with screen diameters of 500 μm and 250 μm were not used for the cleaned coal concentrate. The results indicate that the coal samples from the study area have improved carbon content and low ash content. The highest product yield of 35.15% was obtained at the liberation size of 125 microns. The coal grade in the study area is classified as bituminous coal type, with a carbon content of 79.47%.

Declarations

Conflicts of Interest

There are no conflicts of interest.

Ethical Statement

The research was carried out in accordance with ethical standards.

Funding

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