

## Research Article

# The Flotation Response of Dedo Coal Deposit, Jimma, Ethiopia: Implication to Improve the Quality of Coal

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## Abstract

Ethiopia possesses considerable coal resources, but their low grade, marked by high ash and moisture, restricts industrial utilization. This work examined how run-of-mine coal from the Dedo deposit in Jimma Zone, south-western Ethiopia, responds to froth flotation, with the goal of raising its quality. Duplicate batch tests were run in a laboratory Wedag flotation cell to assess how particle size ( $-500+250\ \mu\text{m}$  and  $-125+63\ \mu\text{m}$ ) and impeller speed (1500 and 2500 rpm) influence concentrate yield. Kerosene served as the collector and n-octanol as the frother, and the feed mass, conditioning time and reagent dosages were kept fixed. Proximate analysis, sulfur content and calorific value were used to characterize both the raw coal and the floated concentrate. Mean concentrate yield varied from 48.0% for the coarse fraction at 1500 rpm up to 66.5% for the fine fraction at 2500 rpm, which shows that, within the ranges tested, finer particles and a higher impeller speed improved flotation. Compared with the raw coal, the concentrate produced under the best conditions contained less ash (25.66% to 20.28%), moisture (13.63% to 11.06%), volatile matter (33.45% to 25.63%) and sulfur (0.36% to 0.25%), and had a higher calorific value (4806 to 5029.38 cal/g), while fixed carbon increased (27.26% to 43.03%). The findings suggest that froth flotation can give a cleaner, more energy-rich product from Dedo coal; however, the calorific value gain was small (about 4.6%), and only two levels of two variables were investigated. Before process conditions for industrial use can be defined, the effects of collector and frother dosage, solids concentration, pH, air flow rate and conditioning time, as well as the composition of the flotation tailings, still need to be assessed.

## Keywords

Froth Flotation, Dedo Coal Deposit, Flotation Response, Particle Size, Impeller Speed, Coal Beneficiation, Low-Rank Coal

## 1. Introduction

Coal is an organic sedimentary rock made up mainly of carbon, hydrogen, and oxygen. It forms when buried plant material is gradually transformed by heat and pressure over geological time. Worldwide reserves are put at more than 909 billion tonnes, which is enough to satisfy present demand for

over 150 years. The countries holding the largest reserves are the United States, Russia, China, India, South Africa, Ukraine, Serbia, Mongolia, and Brazil. Africa's most important coal deposits are located in South Africa, while Ethiopia's resources are estimated at roughly 300 million tonnes [1]. Coal

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Received: 25 September 2026; Accepted: 13 October 2026; Published: 29 October 2026



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continues to be a vital raw material for generating electricity, producing steel and cement, manufacturing activated carbon, and making liquid fuels.

Froth flotation separates particles according to the degree to which their surfaces repel water. Hydrophobic, carbon-rich particles attach to air bubbles and rise into the froth, whereas hydrophilic mineral matter stays behind in the slurry [2, 3]. The floatability of a coal is governed by its petrographic and mineral composition, its rank, its degree of oxidation, and the nature and amount of the inorganic impurities present [4, 5]. Low-rank coals such as lignite are particularly difficult to float cleanly, since they are rich in oxygen, highly porous and bear many polar functional groups on their surfaces [6, 7]. As a result, reagent selection has attracted considerable research attention, and hydrocarbon oils, surfactants and carboxylic acids have all been investigated as collectors and modifiers [8-11].

Apart from reagent chemistry, particle size and the hydrodynamic environment in the cell strongly affect flotation performance. Coarse particles tend to detach from bubbles, while very fine particles collide with bubbles less efficiently and are prone to entraining mineral matter into the froth [12-14]. In a mechanical cell, the impeller speed sets the energy input, the bubble size and the degree of bubble dispersion, and hence the likelihood that particles and bubbles come into contact [15, 16]. Gravity-based equipment, including water-only cyclones, has likewise been applied to coal fines [17], but flotation remains the principal technique for cleaning fine coal.

The flotation of coal from south-western Ethiopia has been

investigated for the Achibo-Sombo-Dabaso area [18]. To the authors' knowledge, however, the flotation behavior of the Dedo deposit has not been meaningfully studied. Because Ethiopia lacks high-grade coal, there is good reason to upgrade its abundant low-grade resources. The general objective of this study was to establish how Dedo coal responds to flotation and to recover the fine coal particles present in the slurry. Its specific objectives were (i) to increase the flotation recovery of the more hydrophilic coal particles and (ii) to raise the quality of the fine coal fraction by reducing its impurity content. The work concentrated on the influence of particle size and impeller speed on flotation performance. The findings are expected to benefit RIALMINE Trading PLC and other companies interested in processing Dedo coal by providing operating parameters that help overcome practical flotation problems.

#### *Study Area and Geological Setting*

The Dedo coal deposit lies in the Jimma Zone of south-western Ethiopia, about 415 km south-west of Addis Ababa, and covers an area of roughly 194 km<sup>2</sup> (Figure 1). It ranks among the country's most significant coal reserves, with an estimated 430 million tonnes of coal in place. Exploration and development have been carried out jointly by East Africa Metals, a Vancouver-based mineral exploration company, and the Ethiopian Ministry of Mines, Petroleum and Natural Gas. Exploration began in 2018, and promising results on both the quality and quantity of the coal were reported the following year.

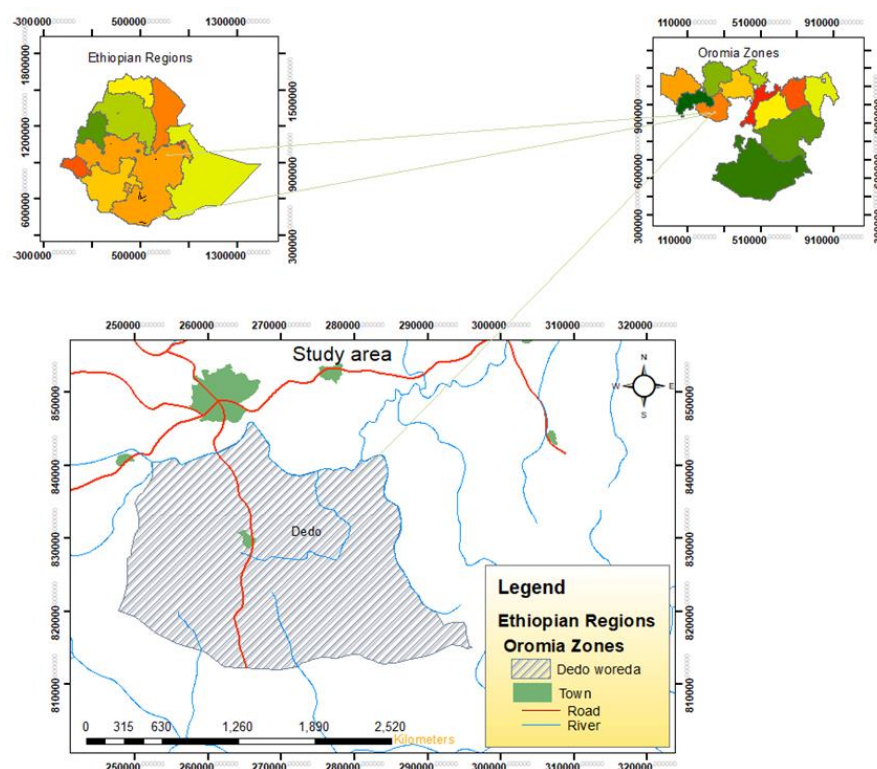


**Figure 1.** Map showing the location of the study area: (a) regions of Ethiopia, (b) zones of Oromia and (c) Dedo woreda.

In geological terms, the Dedo coal basin is underlain by volcanic and sedimentary rock units, along with a few minor, localized intrusive and pyroclastic occurrences (Figure 2). The volcanic rocks range widely in composition, from basic to acidic. The host sequence dates from the Neoproterozoic to the Cretaceous and consists of sandstones, shales, siltstones, and limestones. The coal-bearing formation lies within the

Adola Belt, a north-west-trending tectonic zone about 400 km long that crosses southern Ethiopia and is especially known for its gold and base-metal mineralization [19, 20]. The Adola Belt is made up of several sub-belts, including the Moyale, Mega, and Kenticha sub-belts, and the sedimentary rocks hosting the Dedo coal diposit belong to the Kenticha sub-belt.

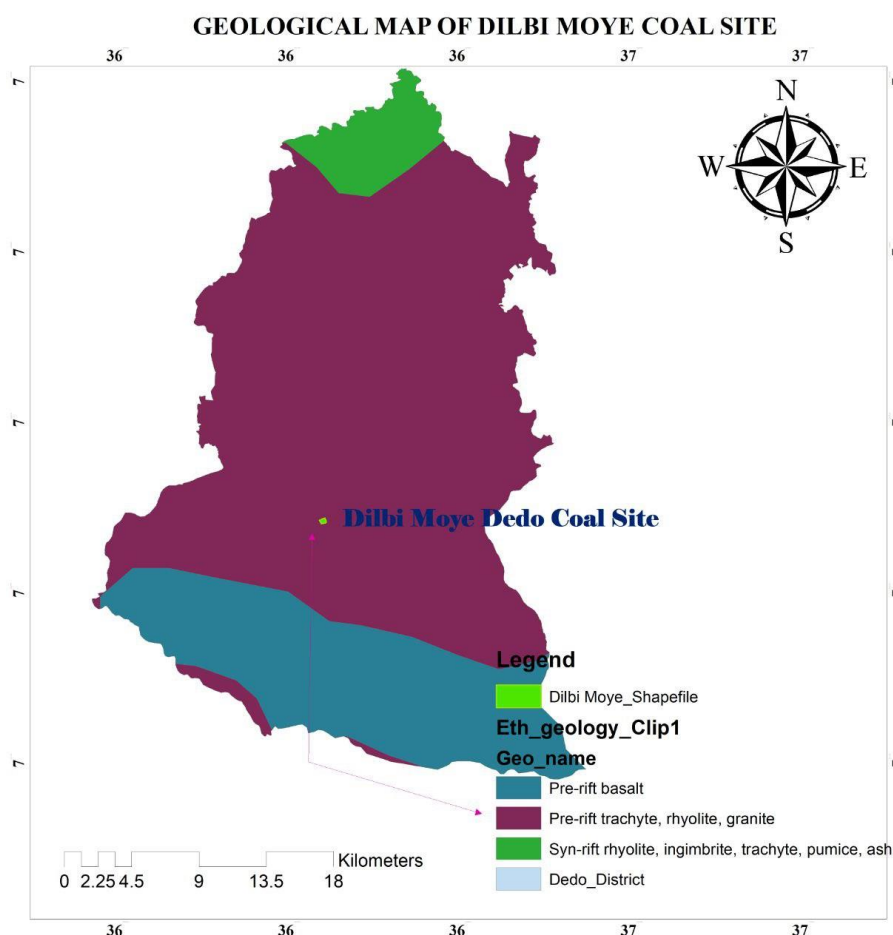


**Figure 2.** Geological map of the study area.

## 2. Materials and Methods

Prior to the experiments, a review was made of the literature, scientific journals, books and secondary data from companies and the Ethiopian Geological Institute. A bulk coal sample was subsequently collected and prepared, and laboratory flotation tests and coal quality analyses were performed to characterize the flotation response of the Dedo coal deposit.

### 2.1. Materials and Equipment

The test material was run-of-mine coal from the Dedo coal deposit. The equipment consisted of a laboratory jaw crusher (RoHS 53743), a laboratory centrifugal mill, sieves of various mesh sizes with an automated vibrating sieve shaker, and a laboratory Wedag flotation cell (Groppel 98) (Figure 3). Kerosene was used as the collector and n-octanol as the frother. Table 1 summarizes the laboratory set-up.



(A)



(B)



(C)



(D)

**Figure 3.** Equipment used in the laboratory: (A) jaw crusher, (B) centrifugal mill, (C) sieves and (D) Wedag flotation cell.

**Table 1.** Overview of the laboratory set-up.

| Item              | Description                                                                    |
|-------------------|--------------------------------------------------------------------------------|
| Material          | Run-of-mine coal                                                               |
| Sample origin     | Dedo coal deposit, Jimma, Ethiopia (open pit operated by RIALMINE Trading PLC) |
| Crusher           | Jaw crusher                                                                    |
| Mill              | Centrifugal mill (one mill)                                                    |
| Variables studied | Particle size and impeller speed (two variables)                               |
| Reagents          | Kerosene (collector); n-octanol (frother)                                      |

## 2.2. Sample Collection and Preparation

A bulk coal sample of roughly 5 kg was collected from the open pit mine run by RIALMINE Trading PLC. The sample was crushed and ground, then separated by particle size using a stack of sieves on an automated vibrating sieve shaker, with the sieves arranged from the largest aperture at the top to the smallest at the bottom. Two size fractions were used for the flotation tests:  $-500+250\ \mu\text{m}$  (coarse) and  $-125+63\ \mu\text{m}$  (fine).

## 2.3. Flotation Experiments

In each test, 100 g of the coarse or fine fraction was combined with 2 L of tap water and agitated for 3 min at the chosen impeller speed (1500 or 2500 rpm) with the air valve shut, until the coal particles were fully wetted. Next, 5 mL of kerosene was introduced as collector and the pulp was conditioned for another 3 min. n-Octanol was then added as frother at 40 parts per million (ppm) (0.12 mL), and the air valve was opened to feed air into the cell. When bubbles began to form, 1 L of water was added to bring the cell up to its working volume. The bubble-particle aggregates overflowed from the cell, and the floated product was collected. Collection of froth went on until white froth appeared, which marked the end point of flotation.

The concentrate was filtered and then dried in an oven at  $80\ ^\circ\text{C}$  for 3 h. For every test, the yield of floated concentrate was computed with Equation (1):

$$\text{Yield (\%)} = \frac{M_c}{M_f} \times 100 \quad (1)$$

where  $M_c$  is the mass of the dried concentrate (g) and  $M_f$  is the mass of the feed (g). The experiments followed a two-factor, two-level design (particle size  $\times$  impeller speed), with each combination run in duplicate while the feed mass, conditioning time and reagent dosages were kept constant. The best condition was chosen by comparing mean yields.

## 2.4. Proximate Analysis, Sulfur and Calorific Value

The raw coal, and the concentrate produced under the best flotation condition ( $-125+63\ \mu\text{m}$ , 2500 rpm), were analyzed for moisture, ash, volatile matter and fixed carbon according to American Society for Testing and Materials (ASTM) procedures, described below. Sulfur content and calorific value were also measured for both samples.

### 2.4.1. Moisture Content

Total moisture was measured following ASTM D-3302. Two grams of air-dried fine coal were put in a silica crucible

and heated in an oven at  $107\ ^\circ\text{C}$  for 3 h. After cooling in a desiccator, the sample was weighed again, and moisture content was calculated with Equation (2):

$$\text{Moisture content (\%)} = \frac{\text{Loss in weight}}{\text{Weight of sample taken}} \times 100 \quad (2)$$

### 2.4.2. Ash Content

Ash content was measured following ASTM D-3174. One gram of sample was weighed into a silica crucible and heated, uncovered, in a muffle furnace at  $850 \pm 5\ ^\circ\text{C}$  for 3 h. The residue was cooled in a desiccator and weighed again, and ash content was calculated with Equation (3):

$$\text{Ash content (\%)} = \frac{\text{Weight of ash residue}}{\text{Weight of dried coal sample}} \times 100 \quad (3)$$

### 2.4.3. Volatile Matter

Volatile matter was measured following ASTM D-3175. One gram of air-dried sample was weighed into a silica crucible fitted with a lid to prevent oxidation, and heated in a muffle furnace at  $950 \pm 5\ ^\circ\text{C}$  for exactly 7 min without air. The sample was cooled in a desiccator and reweighed, and volatile matter was calculated with Equation (4):

$$\text{Volatile matter (\%)} = \frac{\text{Loss in weight}}{\text{Weight of sample taken}} \times 100 - \text{moisture content (\%)} \quad (4)$$

### 2.4.4. Fixed Carbon

Fixed carbon was obtained following ASTM D-388 by subtracting the combined moisture, volatile matter and ash contents from 100, as given in Equation (5):

$$\text{Fixed carbon (\%)} = 100 - (\text{moisture} + \text{volatile matter} + \text{ash}) \quad (5)$$

## 3. Results

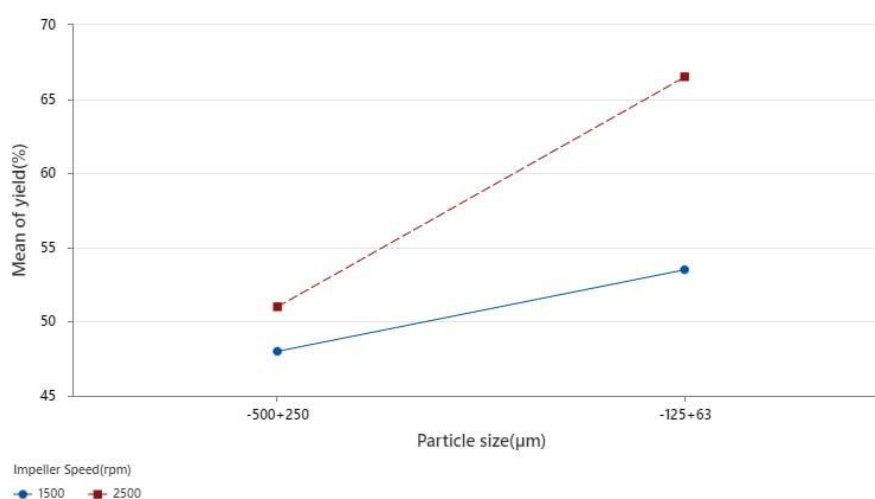
### 3.1. Effect of Particle Size and Impeller Speed on Yield

Table 2. Lists the yields from the eight flotation experiments, and the mean yields of the duplicates are plotted in Figure 4. Duplicates agreed to within 1-2 percentage points. Individual yields spanned 47% (run D11,  $-500+250\ \mu\text{m}$  at 1500 rpm) to 67% (run D41,  $-125+63\ \mu\text{m}$  at 2500 rpm). Mean yields were 48.0% (coarse) and 53.5% (fine) at 1500 rpm, and 51.0% (coarse) and 66.5% (fine) at 2500 rpm.

**Table 2.** Results of the coal flotation experiments.

| Sample code | Particle size ( $\mu\text{m}$ ) | Impeller speed (rpm) | Feed (g) | Concentrate (g) | Yield (%) |
|-------------|---------------------------------|----------------------|----------|-----------------|-----------|
| D11         | –500+250                        | 1500                 | 100      | 47              | 47        |
| D12         | –500+250                        | 1500                 | 100      | 49              | 49        |
| D21         | –125+63                         | 1500                 | 100      | 53              | 53        |
| D22         | –125+63                         | 1500                 | 100      | 54              | 54        |
| D31         | –500+250                        | 2500                 | 100      | 50              | 50        |
| D32         | –500+250                        | 2500                 | 100      | 52              | 52        |
| D41         | –125+63                         | 2500                 | 100      | 67              | 67        |
| D42         | –125+63                         | 2500                 | 100      | 66              | 66        |

A code ending in 1 or 2 indicates the first or second duplicate of that condition.

**Figure 4.** Influence of particle size and impeller speed on the mean yield of floated coal.

Reducing the particle size increased the mean yield at both impeller speeds (by 5.5 percentage points at 1500 rpm and by 15.5 points at 2500 rpm). Raising the impeller speed increased the mean yield for both fractions (by 3.0 points for the coarse fraction and 13.0 points for the fine fraction). Accordingly, the highest yield came from the finest fraction at the highest speed, and the lowest yield from the coarsest fraction at the lowest speed. Table 3 summarizes the conditions that gave the highest yield among those tested.

**Table 3.** Conditions that produced the highest coal yield of those tested.

| No. | Parameter     | Value |
|-----|---------------|-------|
| 1   | Feed mass (g) | 100   |

| No. | Parameter                       | Value                         |
|-----|---------------------------------|-------------------------------|
| 2   | Particle size ( $\mu\text{m}$ ) | –125+63                       |
| 3   | Impeller speed (rpm)            | 2500                          |
| 4   | Yield of concentrate (%)        | 67 (mean of duplicates: 66.5) |

### 3.2. Flotation Observations

Once kerosene was added, large bubbles formed and the coal particles did not adhere to the oily bubble surfaces (Figure 5A). After n-octanol was added and flotation proceeded for about 5 min, the bubbles became smaller and more stable, and coal particles attached to them (Figure 5B). The froth concentrate was filtered and oven-dried at 80°C for about 3 h before proximate analysis (Figure 5C).



**Figure 5.** Froth flotation procedure and the resulting coal particles: (A) after adding the collector, (B) after adding the frother, (C) filtered concentrate.

### 3.3. Coal Quality Before and After Flotation.

Table 4. And Figure 6 present the proximate analysis results, sulfur content and calorific value of the raw coal and the floated concentrate. Following flotation, ash content dropped

from 25.66% to 20.28% (a decrease of 5.38 percentage points, about 21% in relative terms), moisture from 13.63% to 11.06%, and sulfur from 0.36% to 0.25%. Calorific value rose from 4806 to 5029.38 calories per gram (cal/g) (an increase of 223.38 cal/g, about 4.6%). Volatile matter fell from 33.45% to 25.63%, while fixed carbon climbed from 27.26% to 43.03%.

**Table 4.** Proximate analysis, sulfur content and calorific value of the raw and floated Dedo coal.

| Sample              | Ash (%) | Volatile matter (%) | Moisture (%) | Fixed carbon (%)<br>a | Sulfur (%) | Calorific value (cal/g) |
|---------------------|---------|---------------------|--------------|-----------------------|------------|-------------------------|
| Raw coal            | 25.66   | 33.45               | 13.63        | 27.26                 | 0.36       | 4806                    |
| Floated concentrate | 20.28   | 25.63               | 11.06        | 43.03                 | 0.25       | 5029.38                 |

<sup>a</sup>Calculated by difference (Equation (5)).

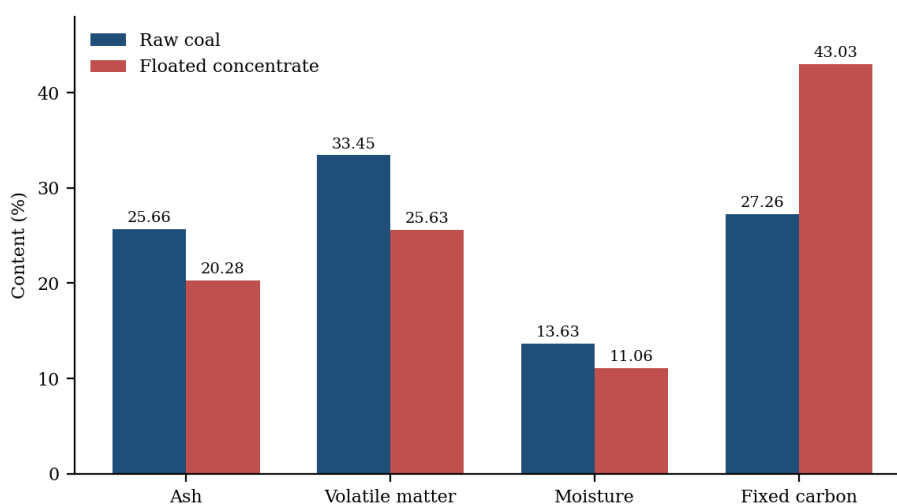


**Figure 6.** Proximate analysis results for the raw coal and the floated concentrate.

## 4. Discussion

### 4.1. Effect of Particle Size and Impeller Speed

Both variables affected concentrate yield. The coarse fraction gave the lowest yields at both impeller speeds and the fine fraction the highest, consistent with reports that particle size is a first-order variable in coal flotation kinetics and recovery [12, 14]. A plausible reason for the lower yield of coarse particles is that they detach more readily from bubbles in a turbulent cell, although detachment was not measured here. Impeller speed had a far larger effect on the fine fraction (13.0 percentage points) than on the coarse fraction (3.0 points), indicating an interaction between the two variables. A higher impeller speed increases energy input and air dispersion and promotes particle-bubble contact [15, 16], and low-inertia fine particles may gain the most from such conditions.

The highest yield was obtained at the finest size and highest speed tested, so the true optimum may lie outside the range examined; particles finer than 63  $\mu\text{m}$  and speeds above 2500 rpm were not tested, and fine particles are known to pose their own difficulties [13]. Moreover, yield in this study is the concentrate mass expressed as a percentage of feed.

### 4.2. Improvement in Coal Quality

Moisture dropped from 13.63% to 11.06%. High moisture reduces the heating value and increases transport and storage costs [21]. Since the concentrate was oven-dried at 80  $^{\circ}\text{C}$  for 3 h before analysis, some of this decrease may be due to drying and not to flotation itself; a like-for-like comparison would need the raw coal to be treated the same way.

The fall in ash from 25.66% to 20.28% is the clearest sign of upgrading, since flotation separates hydrophobic carbonaceous matter from hydrophilic mineral matter. High ash lowers combustion efficiency and raises handling costs. At high temperatures coal ash turns sticky and ultimately forms molten slag, and ash behavior influences the design of ash-handling systems in coal utilization. Sulfur content, already low, declined from 0.36% to 0.25%, which is favorable for combustion emissions.

Volatile matter declined from 33.45% to 25.63%, and fixed carbon rose from 27.26% to 43.03%, a gain of 15.77 percentage points. Because fixed carbon was calculated by difference (Equation (5)), it increases whenever ash, moisture and volatile matter all decrease, as happened here. High volatile matter is generally associated with lower-rank coal. The calorific value increased by only about 4.6% (from 4806 to 5029.38 cal/g), which is less than the change in fixed carbon might lead one to expect. As the concentrate was dried before analysis and the raw coal may not have been, the proximate values of the two samples may not share the same moisture basis, which could partly explain the discrepancy. The comparison should be verified by analyzing both samples on the same basis.

Usman et al. [18] reported, for coal from the Achibo-Sombo-Dabaso area, also in south-western Ethiopia, that flotation using diesel oil as collector and n-octanol as frother, at various reagent dosages and particle sizes, lowered ash from 22.47-36.58% to 7.49-13.62% and raised calorific value from 3243.59-5295.34 to 5243.40-6531.46 kcal/kg (numerically equal to cal/g).

## 5. Conclusions

This research examined how coal from the Dedo deposit responds to flotation, focusing mainly on froth flotation methods. The goals were to improve the flotation of coal particles that are more hydrophilic in nature, such as lignite and lignite-to-bituminous coal, to raise the quality of fine coal by lowering its impurity content (ash, mineral matter, and sulfur), and to determine how particle size and impeller speed influence coal flotation.

The findings show that both coal particle size and impeller speed can have a considerable effect on flotation performance. Other variables also influence the process, including solids percentage, air flow rate, collector type and dosage, frother type and dosage, slurry pH, and conditioning time, but these were not examined in this project. Any negative effects from these variables could be managed by modifying the processing mechanisms.

Coal quality also improved after beneficiation. The calorific value rose from 4806 cal/g in the raw coal to more than 5000 cal/g in the treated coal. This suggests that ash, mineral matter, and sulfur were reduced and that the heating value increased as a result of effective froth flotation. It can therefore be concluded that the project increased the carbon content of the Dedo coal, producing a coal suitable for use as an energy source in the cement and steel industries.

## Abbreviations

|       |                                            |
|-------|--------------------------------------------|
| ASTM  | American Society for Testing and Materials |
| AAiT  | Addis Ababa Institute of Technology        |
| cal/g | Calories Per Gram                          |
| ppm   | Parts Per Million                          |
| rpm   | Revolutions Per Minute                     |

## Acknowledgments

The authors thank the Addis Ababa Institute of Technology (AAiT), School of Chemical and Bio-Engineering, for allowing the use of its laboratory facilities and for technical support during the experimental work. The extended gratitude to the ministry of mines for its comprehensive sponsorship and logistical support during fieldwork. The authors also appreciate RIALMINE Trading PLC for sharing data that were essential to this study.

## Author Contributions

**Dejene Amame:** Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft

**Melesse Alemayehu:** Supervision, Validation, Writing – review & editing

## Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

## Conflicts of Interest

The authors declare no conflicts of interest.

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