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Investigating the Characterization and Grindability Behaviour of Farin-lamba Cassiterite toward Effective Tin Oxide Production

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Cassiterite has been an essential source of tin; its exploration and exploitation have become a priority worldwide. The effective beneficiation of cassiterite depends mainly on its grindability and effective liberation. The Modified Bond's grindability test is a method used to determine the work index, which is crucial in estimating the energy needed to grind an ore. This is crucial during mineral processing, as a slight deviation would affect the company's operating expenditure (OPEX). This study investigates the work index for Farin-Lamba cassiterite with reference to silica sand sourced from Igbokoda. The test ore (cassiterite) was analyzed using Energy Dispersed X-ray

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fluorescence spectrometer (ED-XRS), Petrographic Analysis, and Scanning Electron Microscope equipped with an Energy Dispersive Spectrum (SEM-EDS) to understand their chemical and mineralogical characteristics in relation to their grindability. The test ore and the reference material (silica sand) underwent comminution using 500g of each to a 100% passing 500 µm array of sieves arranged in (√2) series from 500µm to 63µm onto an automatic sieve shaker. The chemical and mineralogical analysis revealed the presence of gangue such as SiO2 and Al2O3, which increases the energy needed during communition; further, the presence of rough and large grain size in the ore also increases the energy needed for communition. The results were subjected to Gaudin Schuman's equation to determine the ore's work index, which was 14.664 KWh/ton for the test ore, which is standard for cassiterite, which ranges from 10-15 kWh/ton. Further, the energy needed for comminution was calculated to be 33.7272 Kwh, providing valuable insights into the energy efficiency of the grinding process. The evaluation of the grindability of Farin-Lamba cassiterite in relation to the reference ore not only contributes toward understanding the ore processing dynamics but also provides information needed for the optimization of energy consumed during the process of tin oxide production.

Keywords: Cassiterite; characterization; bonds equation; grindability; work index; comminution optimization; tin oxide; mineralogy; geochemistry.

1. INTRODUCTION

Tinstone, also known as cassiterite, is a mineral that is translucent in its pure form but turns brownish-blackish when iron, aluminium, and silica impurities are present. Cassiterite has a 78.6% tin oxide percentage when chemically pure but is generally uncommon. However, when it is impure, the tin content can range from 40 % to 55%. There exist two basic kinds of deposits containing cassiterite; firstly, it is present in veins and fissures in the granite and adjacent parent rocks and is the principal constituent of some late-stage granitic intrusions. Secondly, the deposit occurs in secondary origin and can be found as detrital, placer, or alluvial deposits. Tin oxide (SnO_2) is a substance utilized in many different sectors worldwide, including electronics, ceramics, and coatings, and is a necessary component of modern technology [1,2].

Nowadays, the majority of cassiterite's sources are alluvial deposits containing weathered grains rather than primary deposits; Malaysia, Bolivia, Indonesia, Belgium, Congo, and Nigeria account for the majority of the world's supply of tin ore. Cassiterite has been an important source of tin for various metallurgical applications and is still the greatest source of tin today. The exploitation of mineral resources has become a top priority in many developing nations, leading to the depletion of high-grade ores [3]. Nigeria, for example, has abundant mineral resources, such as iron ore, manganese, copper, and coal, that have significantly increased the country's gross domestic product (GDP), bringing about socioeconomic benefits. The production of tin oxide depends on the efficient beneficiation of cassiterite, which must first go through a comminution process that involves ore crushing and grinding. Therefore, knowing the ore's grindability is an important step toward the efficient and effective production of tin oxide [4].

It is essential to understand the geochemistry and mineralogy of minerals as it help address problems associated with beneficiation and concentration. Thomas et al. [5] pointed out some crucial attributes that need to be considered, such as characteristics of the elements in the mineral ore, bulk modal mineralogy, grain size, texture, and association. These important features are limited and need to be considered as ore mineralogy is a complex and intricate, but it contribute primarily to deciding the best separation process. Characterizing the element of interest within the minerals present in the ore to define the elements' entitlement is the first step in identifying the mineralogical limit to separation. This can be achieved by making use of the combination of the new advanced automated scanning electron microscopy technique, which helps point out the elemental composition and in-depth ore characteristics [6,7].

The goal of the comminution circuit in mineral processing is to prepare the ore as a suitable feed for separation processes, which upgrade the material by rejecting the particles that do not contain economically significant amounts of the target mineral. Comminution theory deals with the relationship between energy input into particle size reduction and the particle size distribution from a given feed size. In contrast, grindability tests seek to estimate the energy consumption of grinding and to give parameters for the grinding mill sizing using various test methods. The communition process significantly converts the ore from a population of particles with a relatively uniform grade to particles with a range of compositions that allow them to be separated into low-grade and high-grade streams [1,8].

Insufficient mineral liberation during the separation phases of an ore is a result of grinding it to excessively coarse particle size. However, grinding the mineral too fine results in higher grinding costs and possibly low final recovery. Thus, efficient grinding is one of the most important components of effective mineral processing. Energy consumption drives the cost of grinding. Extensive grinding might not always be a disadvantage because the earlier steps might compensate for the higher energy use. While the primary goal of grinding is to achieve the economic degree of release, grinding is also occasionally employed to enhance the surface area of minerals [9].

The most energy-intensive step in mineral processing is grinding, which comes at the end of the comminution process and can cost a mineral processing plant more than half its operating expenses. The goal of grinding is the economic degree of liberation of the target mineral. Thus, understanding an ore's comminution qualities is crucial whether running a mineral processing facility or carrying out a feasibility assessment [10].

While tumbling mills have reached a high level of mechanical efficiency and dependability, there is ongoing discussion on their energy efficiency. The main issue with tumbling mills and all other crushing and grinding equipment is that very little of the energy input is used to break the ore because the equipment consumes the majority. Less than 1% of the entire energy input is available for size reduction, with most of the energy being used to produce heat, as demonstrated by Wills et al. [11].

The primary objective of this research is to understand the mineralogical and chemical characteristics and evaluate the grindabilty behavior of Farin-Lamba cassiterite using the modified Bonds Index for effective beneficiation. Understanding the grindability and the ore composition can pave the way for the optimization of processing circuits to enhance sustainable tin oxide production.

2. MATERIALS AND METHODS

2.1 Materials

The samples for this research came from Farin-Lamba mines, situated in Plateau State, Nigeria's Jos South Local Government Area, collected from different pits tagged Pit LCA-1, LCA-2, LCA-3, LCA-4, and LCA-5.

2.2 Methods

A Denver Laboratory Milling Machine (D-12) was used to grind the samples to determine their liberation size and conduct mineralogical and elemental analysis of the crude material. After crushing and grinding, the reference ore, Igbokoda silica, and the test ore were charged into a set of sieves and left on an automatic sieve shaker for 20 minutes. Weighing the sieve fractions of the test and reference ore that was retained allowed us to record the feed product's value for work index calculations.

The processed samples underwent mineralogical characterization by utilization of an X-ray Diffractometer (XRD) (Model: PANanalytical Minipal 7), a Scanning Electron Microscope equipped with a Dispersion Spectrum (SEM-EDS) (Model: QEMSCAN), and a Petrological Analyzer (Model: Leica EGB 100). Finally, the modified Bond's Equation [12] was used to determine the theoretical work index of cassiterite, which involves using reference material such as silica whose grindability is known, as shown in Equation 1-2.

$$\text{Wit} = \text{Wir}\left(\frac{10}{\sqrt{\text{P}}} - \frac{10}{\sqrt{\text{F}}}\right) \tag{1}$$

$$\text{Wit} = \text{Wir}\left(\frac{\frac{10}{\sqrt{\text{Pr}}} - \frac{10}{\sqrt{\text{Fr}}}}{\frac{10}{\sqrt{\text{Pt}}} - \frac{10}{\sqrt{\text{Ft}}}}\right) \tag{2}$$

Where Wit is the test ore Work Index, Wir is the reference ore Work Index, Pr is the reference ore where 80% of the materials pass 100µm, Pt is the test ore diameter where 80% of the materials pass 100µm, Fr is the reference ore diameter where 80% of the feed pass 100µm, Ft is the test ore diameter where 80% of the feed pass 100µm, Wr is the reference ore work input and Wt is the test ore work input [13].

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Elemental analysis of the cassiterite sample

Table 1. Chemical composition of the crude cassiterite

Compounds	Al_2O_3	SnO_2	Ta_2O_5	SiO_2	Fe_2O_3	BaO	SO_3	ZrO_2	TiO_2	Nb_2O_3	CaO
Composition %)	5.450	24.720	0.667	49.980	3.500	2.136	1.651	2.550	4.600	1.036	1.785

3.1.2 Mineralogical characterization examination using a scanning electron microscope with an energy-dispersive spectrum (SEM-EDS)

a. SEM micrograph of crude cassiterite

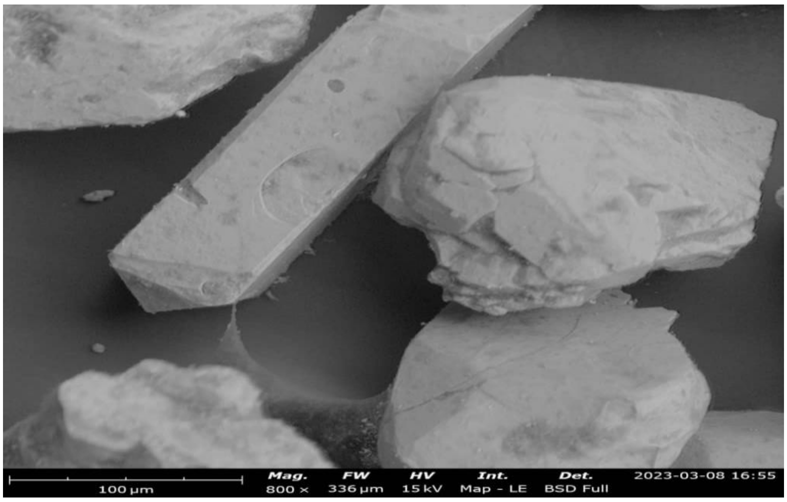

Fig. 1. Scanned Electron micrograph of crude cassiterite sample

b. EDS phase diagram of crude cassiterite

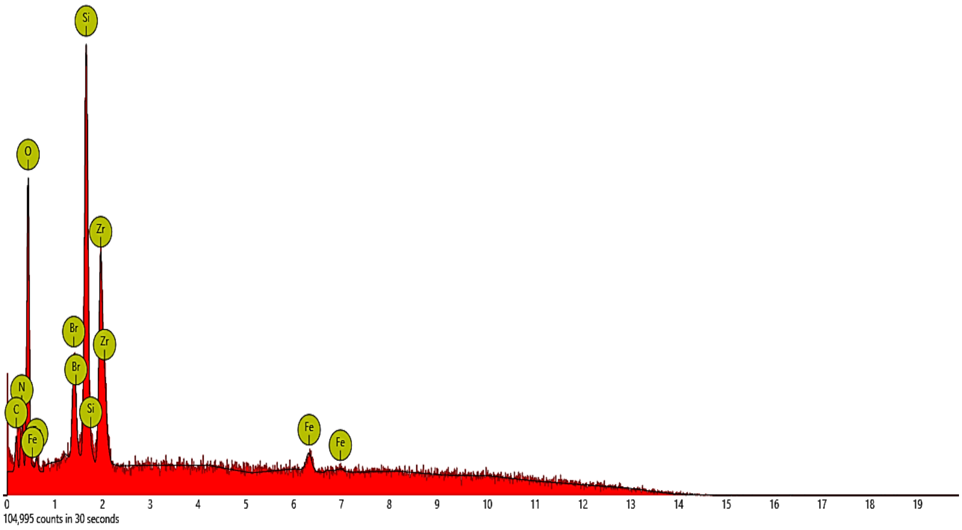

Fig. 2. EDS of crude cassiterite at 500 µm magnification

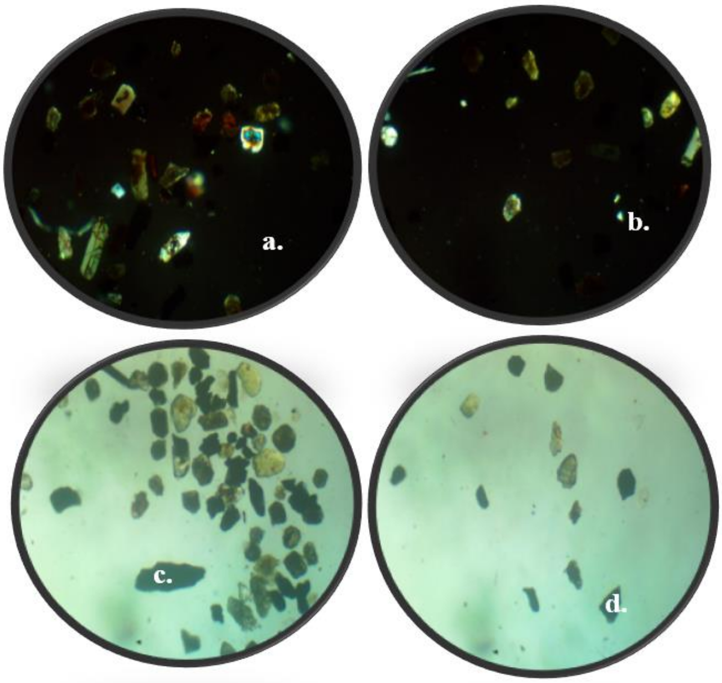

Fig. 3. Petrographs of crude cassiterite at 500 magnification in PPL and XPL

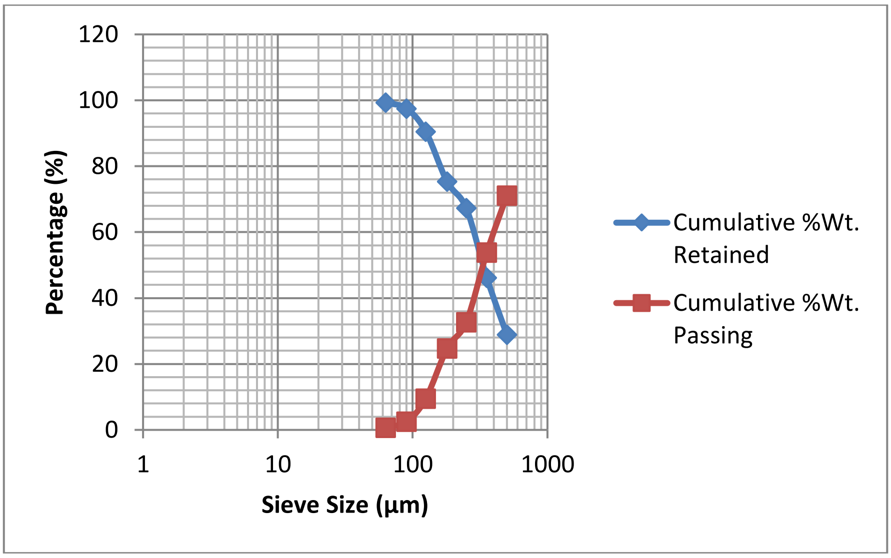

Fig 4. Plot of % cumulative retained and passing against sieve sizes (test ore fed to the ball mill)

3.1.3 Petrological analysis

The minerals contained in the test ore were identified using optical techniques in both cross-polarized light (XPL) and plane-polarized light (PPL), as shown in Fig. 3.

3.1.4 Particle size analysis

The sieve analysis plots of the test (cassiterite) and reference ore (silica sand) feed to the ball mill are displayed in Figs. 4–7. They plot different varied sieve sizes against the cumulative percentage of the ore retained, and the cumulative percentage of the ore passed.

3.1.5 Grindability evaluation

Equation 4 was used to evaluate the grindability of the cassiterite.

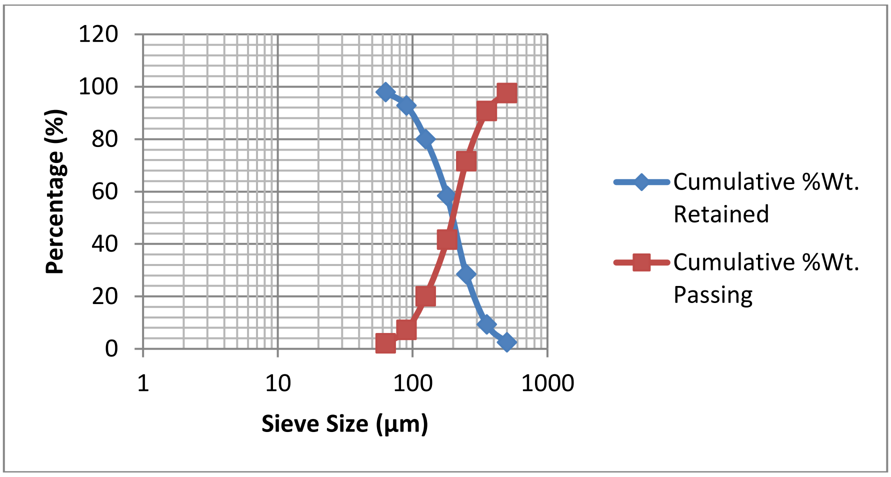

Fig. 5. Plot of % cumulative retained and passing particles against sieve sizes (reference ore fed to the ball mill)

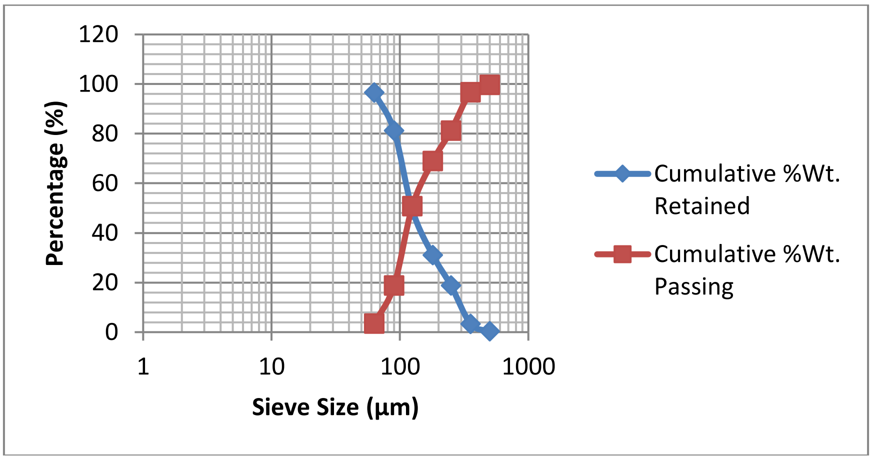

Fig. 6. Plot of cumulative % retained and passing against sieve sizes (test ore product from ball mill)

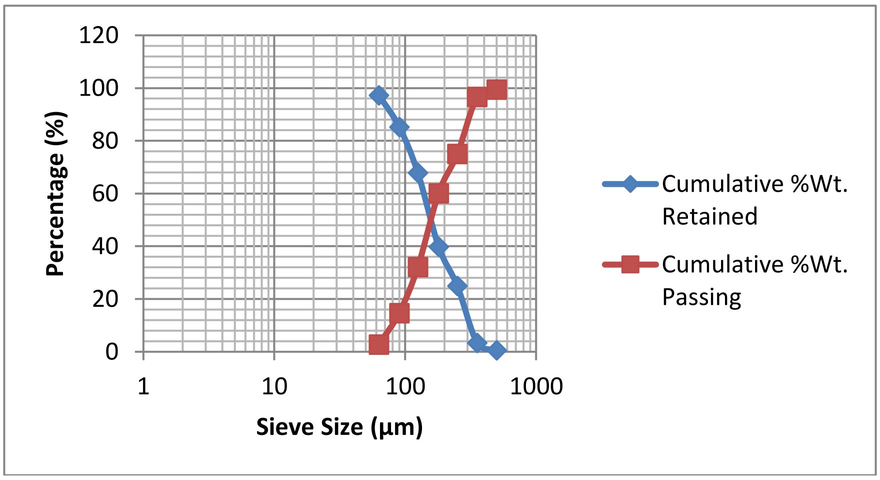

Fig. 7. Plot of cumulative % retained and passing against sieve sizes (reference ore product from ball mill)

Table 2. 500 µm and 250 µm mesh sizes of sieves having an 80% particle size pass rate

Samples	80% Passing Feed µm (F)	80% Passing Milled Product µm (P)
Test Ore (Cassiterite)	592.13	238.66
Reference Ore (Silica Sand)	660.20	250.44

$$R = \frac{F}{P} \tag{4}$$

Where R is the reduction ratio, F is the feed particle diameter, and P is the product particle diameter.

Utilizing Gaudin Schumann's expression as shown in Equations 5-7;

$$P\ (X) = 100\ (X - K)^{\alpha} \tag{5}$$

$$\alpha = \frac{\log P\ (X2) - \log P\ (X1)}{\log(X2) - (X1)} \tag{6}$$

$$Sieve\ 1 = \frac{\%\ Passing\ in\ Sieve\ 1}{\%\ Passing\ in\ Sieve\ 2} \times \text{sieve 2} \tag{7}$$

Where X is the sieve size with 80% particle passing

3.1.6 Work index determination

According to the literature, the Work Index of Silica sand is between 2.65 Kwh/t - 16.46 Kwh/t [12]. Taking 14.1 as the Work Index of Silica sand. Therefore, the determination of the work index involved inputting the values obtained from Table 1 into Equations 1 and 2, resulting in a Wir of 14.664 KWh/ton.

Where Wir = 14.1 Kwh/ton

$$\text{Wit} = 14.1 \times \left(\frac{\frac{10}{\sqrt{250.44}}}{\frac{10}{\sqrt{238.66}}} - \frac{\frac{10}{\sqrt{660.20}}}{\frac{10}{\sqrt{592.13}}} \right) = 14.664 \text{ Kwh/ton}$$

3.1.7 Energy used during grinding

The energy used to obtain the optimal liberation size during the communition process was determined by substituting the test work index in Equation 1.

$$Wt = 10 \times 14.664 \times \left(\frac{1}{\sqrt{238.66}} - \frac{1}{\sqrt{592.13}} \right) = 33.7272 \text{ Kwh}$$

4. DISCUSSION

The chemical composition of the crude cassiterite ore revealed 24.72% SnO_2 (tin oxide), as shown in Table 1, which is the main mineral of interest. There are also considerable amounts of gangue, such as SiO_2 (49.98%) and Al_2O_3 (5.45%), among others. Elements such as SiO_2 contribute to the formation of hard and abrasive grains due to the presence of minerals such as quartz that increase the energy needed during communition and increases also increase the wear and tear during grinding, thereby reducing the grindability of the cassiterite ore.

Figs. 1-2 show a SEM image at 100 µm with 800 magnification, as well as an EDS qualitative analysis of the Farin - Lamba Cassiterite deposit at 500 magnification for Spectrum 1. The SEM morphology reveals that the minerals in the ore matrix are closely packed, allowing for simple liberation via grinding, which is a key and result-determining step in mineral processing, and all subsequent downstream processes in the beneficiation chain rely totally on it [14]. The EDS qualitative analysis of the image revealed that the primary elemental elements of minerals in the ore matrix are *Fe, Sn, O, K, Ca, Al*, and *Si.*

SEM-EDS examines the composition and microstructure of samples at a scale and gives valuable insights into the mineralogical composition of the ore, including the distribution of different mineral phases and the presence of minerals and their gangue constituents in the ore matrix. This information is critical for understanding ore and gangue composition, mineralogy, and texture impact of the grindability of the ore. The presence of abrasive and coarse minerals within the ore affects its grindability by increasing the energy consumption and wear rates of the communition equipment. On the other hand, the absence of such minerals indicates better grindability of the ore.

There also exists a relationship between ore petrography (Fig. 3) and cassiterite grindability. Petrological analysis helps to understand various mineralogical associations, such as particle shape and agglomeration within the ore, which affect liberation. The ore generally displays isotropic characteristics under crossed polarized light microscopy, revealing subhedral grain shape within a network of Si and Fe intrusions within the host rock. The grain arrangement also appears to be loosely packed within the ore matrix, justifying the low energy used during grinding. Though cassiterite exhibits a subhedral shape and generally does not exhibit a complex structure, thus allowing easy grindability,the presence of silica and iron gangue may consequently affect the grindability and increase the energy for liberation.

Most known minerals occur in consolidated forms, and adequate data on the particle sizes at which these minerals exist separately is required to allow the separation of the mineral of interest from others. Fractional sieve size analysis of Farin-Lamba cassiterite revealed that 27.78 g of the total 100 g was retained on 500 µm, 16.53 g on 355 µm, 20.36 g on 250 µm, 7.71 g on 180 µm 14.67g on 125 µm, 6.71 g on 90 µm, 1.71 g on 63 µm, 0.68 g and -63 µm. The cumulative percentage passing following the order of sieve arrangement from the coarsest is obtained as 71.14 %, 53.86 %, 32.71 %, 24.7%, 9.46 %, 2.49%, and 0.71%. The obtained weight retained in grams indicates easy handling and precise results for the laboratory analysis, which is a possibility of separating the particle size fractions.

The sieve analysis results revealed that the 80% passing particle size fractions for the reference (Fr) and test ore (Ft) fed into the ball mill were 632.25 µm and 312.5 µm, respectively, and the 80% passing particle size fractions for the products that came out of the ball mill were 242.25 µm and 284.55 µm, respectively. The plateau condition Farin-Lamba Cassiterite was found to have a work index of 14.664 Kwh/ton and grindability energy of 33.7272 Kwh. This suggests that reducing one ton of the plateau state Farin-Lamba Cassiterite from 80% passing size requires 33.7272 Kwh of energy.

5. CONCLUSION AND RECCOMENDATIONS

Having carried out the experimentation and subsequent discussions. This study has established the viability of the Farin-Lamba cassiterite for tin oxide recovery. From the results obtained, the following inferences were drawn:

i. The chemical composition analysis shows the presence of tin oxide with the 24.72% assay in the ore; there are also high amounts of SiO_2 with a composition of 49.98%, which influences ore grindability.
ii. SEM/EDS shows the morphological structure of the mineral and its crystallography; this reveals the distribution of grain minerals in the ore matrix (coarse), mainly quartz. This enhances grindability, hence reducing the energy needed for effective mineral liberation.
iii. The petrological analysis shows that the grain particles are loosely packed within the ore matrix, consequently aiding its grindability. The results complement the SEM-EDS results.
iv. Farin-Lamba cassiterite work index was computed to be 14.664 Kwh/ton, utilizing a grindability energy of 33.7272 Kwh. The actual work needed to grind an ore is usually less than 1%, as the remaining energy is dissipated as vibration, noise, and heat [15]. Therefore, this justifies the less energy used in cassiterite grinding as the ore is brittle and soft, as revealed in the mineralogical characterization. This parameter serves to help the development of a process for the beneficiation of Farin-Lamba cassiterite ore to the economic and technological development of a nation.

Effective beneficiation depends on the use of effective mineral separation processes that are based on the petrological features of the ore. The utilization of flotation, magnetic separation, and gravity separation techniques can aid in the focused elimination of gangue minerals, thus increasing the cassiterite concentration. Furthermore, energy efficiency must be closely monitored throughout the beneficiation process, which calls for a cautious assessment of the grinding parameters and reduction of heat, noise, and vibration-related energy losses by optimization. The beneficiation of Farin-Lamba cassiterite ore can promote economic development and help achieve the larger objectives of sustainable resource management and technological advancement by taking a comprehensive approach that combines technical optimization with environmental care.

DATA AVAILABILITY

The data used in this research is available upon request.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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