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Susceptibility Examination of Farin-Lamba Cassiterite to Induced Magnetic and Spiral Concentration towards Tin Oxide Production

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ABSTRACT

Cassiterite ore mainly consists of tin oxide (SnO_2), a vital mineral used in metallurgicalapplications. Cassiterite samples were collected within the Farin-Lamba mining site, and 20 kg crude sample was collected. Representative samples were crushed and ground, followed by chemical characterization, susceptibility tests to gravity and magnetic separation, and concentration of the ore using an induced magnetic separator and Humphrey's spiral concentrator. Chemical characterization of Farin-Lamba cassiterite revealed 20.22% $SnO_2$and other gangue minerals. The specific gravity (SG) of the cassiterite was computed to be 5,and the concentration criterion (CC) was 3.25. Magnetic separation on the cassiterite ore was first done using an induced magnetic separator, and resulting non-magnetic products were subjected to gravity separation using a Humphrey's spiral concentrator. The resulting product's composition was determined using energy-dispersive X-ray Fluorescence (ED-XRF), whose analysis revealed a 27.54% increase from a crude assay of 20.22% to a concentration of 73.42%SnO_2 for the cassiterite ore, an assay needed for tin oxide production. This shows a successful beneficiation process, providing insight into the efficiency of the magnetic-gravity separation methods. Consequently, this sheds light on optimal processing routes, which contribute to enhanced mineral processing technologies and unlock the economic benefits of cassiterite ore extraction.

1. Introduction

Nigeria is endowed with diverse mineral resources of high grades and substantially large reserves to sustain industries. Technological development of metal production can serve as a panacea for national security and economic recovery, as well as the fulfilment of SDG Goals. Among the mineral resources are Cassiterite, Columbite, Lead/Zinc, Gold, Iron, Barite, Gypsum, Bitumen, Coal, Clay, Tantalite, Gold, and a host of others [1].Cassiterite ore with the largest deposit in Jos, Plateau State

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(Farin-Lamba), was once the hub of a mining industry that fed European demand for tin through much of the 20th century, but little can be exploited now due to depletion of high grade [2; 3].

Cassiterite, generally opaque and translucent mineral, occurs in thin crystals mainly consisting of tin oxide (SnO_2). Cassiterite has a significant industrial application due to its diverse uses in alloying, packaging, and electronics [4]. Cassiterite's significance lies in its unique crystalline structure, which holds tin atoms in its lattice body. Tin has distinct properties, including a relatively low melting point and high corrosion resistance.

The physical characteristics of cassiterite ore largely influence its extraction process, as the ore is relatively dense and ,therefore, capable of being beneficiated using the gravity separation method [5]. Cassiterite ore is found in significant amounts worldwide in sedimentary, metamorphic, and igneous rock formations. The ore is also widely distributed in pegmatic and hydrothermal veins that are connected to granitic intrusions. It has been discovered that, in comparison to other minerals, cassiterite ore is far more resistant to weathering processes [6].The effective beneficiation of tin from cassiterite ore depends largely on the separation methods, which play a significant role. Magnetic and gravity separation techniques have emerged as the main methods of cassiterite processing due to their effectiveness and efficiency, which lies in sustainability [7].

This research addresses a critical problem in the beneficiation of cassiterite ore from the Farin-Lamba deposit in Plateau State, Nigeria. Despite the abundant provable cassiterite ore reserves in the region(250,000 tons), the lack of optimized extraction process determination poses a significant challenge towards its exploitation. This problem not only impacts the economic viability of mining operations but also contributes to environmental concerns due to inefficient mineral processing practices. Addressing this problem will improve the annual production of tin from cassiterite, which stands at 5,000 tons annually and is considered to be relatively low [5].To scale up the production of tin oxide, there is a need for susceptibility tests for the cassiterite ore for both magnetic and gravity separation [4; 5]. Resolving this problem is of great importance, as it directly influences the sustainability of the mineral extraction from the Farin-Lamba deposit to contribute to Nigeria's economy and align with global efforts for responsible mineral resource management. Furthermore, the findings of this research hold significant implications for the design of a beneficiation process tailored to Farin-Lamba cassiterite ore. This study contributes to advancing the knowledge towards cassiterite ore beneficiation for tin oxide production.

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2. Methods

2.1 Sample Collection and Preparation

Twenty-kilogram (20kg) sample of cassiterite ore was obtained from the Farin-Lamba mines, which contain the tin oxide-bearing ore in Plateau State, Nigeria. Collected samples were properly mixed, weighed, and stored in air-tight zip-locked bags. These samples were then crushed with a laboratory jaw crusher and then ground with a laboratory ball mill. Five grams (5 g) from the prepared sample was used for the chemical compositional analysis in weight percentage using energy dispersive X-ray fluorescence spectrometer.

2.1.1Methodology workflow

The Farin-Lamba Cassiterite ore samples underwent comminution process sand particle size analysis. The sieved ore was then subjected to susceptibility tests using gravity separation with bromoform as the separation media and magnetic separation using an induced magnetic separator to evaluate the response of the ore to each beneficiation method. In addition to the concentration tests, the samples underwent chemical composition analysis to provide comprehensive insights into the characteristics of the ore and the resulting products.

2.2 Gravity and Magnetic Susceptibility Test

The susceptibility test for the gravity separation method was done using 50g of the ore sample, which was mixed with 50ml of bromoform solution in a 150 ml Pyrex measuring cylinder. This mixture was then agitated using a spatula for 5 mins. Further, filtration was done, and the resulting pulp was dried in an oven, awaiting further analysis to determine the chemical composition, specific gravity, and density. The susceptibility test for magnetic separation was done using an induced magnetic separator with an initial charge of 500 g of cassiterite sample fed to the separator. Magnetic concentrate was obtained, and the induced magnetic separator separated the left non-magnetic (gangue) tailing.

Specific Density Determination (SG)

Ten grams (10g) of the sample obtained from the susceptibility test was precisely weighed for analysis. A 50 ml pycnometer bottle was weighed and recorded as M_1; subsequently, 10 grams of the ore sample were carefully introduced into the empty pycnometer bottle, and the combined weight was recorded as M_2, providing the mass of the ore sample. Finally, it was filled with water, and its mass was

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recorded as M_3. The analysis was repeated twice to ensure consistency, and then specific gravity was determined using Equation 1.

$$S.G = \frac{(M_2 - M_1)}{(M_2 - M_1) - (M_3 - M_4)} \quad 1$$

Where:

M_1 is the mass of empty pycnometer bottle (g)

M_2 is the mass of the empty pycnometer bottle + mass of the sample (g)

M_3 is the mass of empty pycnometer bottle + mass of sample + water (g)

M_4 is mass of empty pycnometer bottle + water (g)

Concentration criterion (CC)

The concentration criterion (CC) was evaluated using Equation 1.

$$CC = \frac{D_h - D_f}{D_l - D_f} \quad 2$$

Where:

D_h is the specific gravity of heavy minerals (sink)

D_l is the specific gravity of light mineral (float)

D_f is the specific gravity of separating medium (bromoform)

2.3 Double Ore Concentration of Cassiterite Ore

A double ore concentration method was used to process the cassiterite ore to obtain an optimal grade needed for tin oxide production, which should be ≥ 60 – 65%[8].The two methods used for this method were the magnetic separation method, where the non-magnetic minerals were subjected to spiral concentration. Finally, metallurgical accounting for the resulting products for spiral concentration was done.

2.3.1 Magnetic separation method

Magnetic separation was done using 1000 g each of Farin-Lamba cassiterite of sieve sizes -500+ 355 µm, -355 + 250 µm, -250 + 180 µm, -180 + 125 µm, and -125 + 90 µm were charged into the upper chamber of the permanently induced magnetic separator. The magnetic and non-magnetic materials collected were weighed, and representative samples chemically analyzed to determine the composition.

2.3.1 Spiral concentration

Spiral concentration was done using a Humphreys spiral concentrator where 500g each of Farin-Lamba cassiterite ore of sieve size -500+ 355 µm, -355 + 250 µm, -250 + 180 µm, -180 + 125 µm, and -125 + 90 µm were mixed with 4000ml of water respectively to form slurry with a constant ratio of 1:4. These slurries were charged through onto the spiral concentrator, where the slurry flew down the spirals as the mineral particles settle and sort according to size, shape and specific gravity. The resulting products were allowed to settle down and were

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decanted after 24 hours. The pulp product was filtered, and the cake from the filtering process was dried in a carbonite oven model OV95C at a temperature of 110ºC for the total removal of moisture. The resulting products were then weighed, sampled, and chemically analyzed.

3. Results and Discussion

3.1 Physical Characterization of Crude Cassiterite Ore

The crude cassiterite ore was physically studied, and the findings summarized in Table 1.

Table 1: Physical Characteristics of the Crude Ore

S/No.	Properties	Observations
1.	Color	Reddish-brown to Brownish-black
2.	Streak	White to brownish
3.	Tenacity	Brittle
4.	Lustre	Adamantine- Splendent to Submetallic
5.	Density	High density

Cassiterite ore deposits are usually found within high-temperature hydrothermal veins that are usually associated with granitic intrusions. The ore also contains weathered grains, which are resistant to corrosion and erosion [8]. The comprehensive physical analysis of the ore, as detailed in Table 1, reveals distinctive characteristics exhibiting reddish–brown to black-brown color with white-brown streaks while displaying brittleness of the structure with a bright luster of notable high density.

3.2 Chemical Characterization of Crude Cassiterite Ore

Chemical characterization of the crude sample was done using ED-XRF, and results are presented in Table 2.

Table 2: Chemical Composition of the Crude Cassiterite Ore

Element	Al_2O_3	SiO_2	Fe_2O_3	BaO	SnO_2	SO_3	ZrO_2	TiO_2	Nb_2O_3	CaO	Ta_2O_5
% Composition	3.24	52.19	5.02	0.616	20.22	6.151	3.77	3.38	2.066	0.755	0.766

The chemical analysis of the cassiterite ore provided in Table 2 providing valuable insights into its composition. The predominant presence of SnO_2, containing a composition of 20.22% of the crude ore,

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reveals that the ore's primary composition for Farin-Lamba Ore is tin oxide. There is also the presence of gangue minerals, such as Fe_2O_3 (5.021%), Nb_2O_5(2.066%) and Cr_2O_3(0.001%) along with other trace elements that contribute to the ore composition. Tin is the sought-after element in the ore; however, additional compounds in the ore, such as Fe_2O_3 influence its processing and extraction to methods such as magnetic separation and gravity. The presence of minor elements, such as Nb_2O_5 and Cr_2O_3 could highlight the potential for by-product recovery for intricate mineral processing. These compounds, though present in small concentrations, may have economic value.

3.3 Susceptibility Test

The charge and the chemical composition analysis fromthe susceptibility tests of the cassiterite ore-bearing sample using bromoform was done using ED – XRF and results summarized in Table 3-4.

Table 3: Charge of Cassiterite Ore Samples and Yield

Method	Charge (g)	Sink/Magnetic (g)	Float/Non-Magnetic (g)
Gravity Susceptibility Test	50.00	33.20	16.80
Magnetic Susceptibility Test	500.00	109.00	391.00

Table 4: Chemical composition for Gravity and Magnetic Susceptibility test

Elements	Gravity Susceptibility (% composition)		Magnetic Susceptibility (% composition)	
	Float	Sink	Magnetic	Non-Magnetic
SiO_2	59.860	9.571	11.642	57.711
Fe_2O_3	16.540	10.622	47.687	4.312
Nb_2O_3	3.310	4.005	6.707	0.91
Cr_2O_3	0.019	0.390	0.23	0.001
Ta_2O_5	1.144	2.252	3.412	0.611
TiO_2	1.241	4.072	0.76	0.361
ZrO_2	3.212	3.071	0.671	10.96
SnO_2	7.210	50.022	41.65	32.41
V_2O_5	0.160	0.253	0.273	0.17
NiO_2	0.260	0.181	0.171	0.07

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3.3.1 Specific Density Determination

The specific density of cassiterite ore was determined from the masses as follows: $M_1 = 25.0$ g, $M_2 = 50.0$ g, $M_3 = 95.0$ g, and $M_4 = 75.0$ using Equation 1.

$$SG = \frac{(50.0 - 25.0)}{(50.0 - 25.0) - (95.0 - 75.0)}$$

$$SG = 5$$

3.3.2 Concentration Criterion (CC)

The CC was determined from the specific gravities as follows: $D_h =$ Specific gravity of sink = 5.0, $D_l =$ Specific gravity of light float = 3.36 and, $D_f =$ Specific gravity of bromoform = 2.63 using Equation 2.

$$CC = \frac{5.00 - 2.63}{3.36 - 2.63}$$

$$CC = 3.25$$

Gravity and Magnetic Susceptibility Tests

Results (Table 3 and Table 4) from the chemical analysis of these processed samples from the susceptibility test revealed that SnO_2 composition increases from 22.220% (assay of the crude sample) to 50.022% (sink materials) for the gravity separation susceptibility test. Consequently, on the magnetic susceptibility test, Fe_2O_3 percentage weight was reduced from 5.02% (assay of the crude) to 4.312% (assay of non-magnetic). The chemical composition and the variation in the yield of the charged processed samples obtained from the susceptibility of cassiterite tin oxide ore for the gravity and magnetic method of mineral separation proved that the mineral in the ore is susceptible to both gravity and magnetic separation methods.

Specific Density (SG) and Concentration Criteria (CC) of processed samples

The specific gravity of the cassiterite was 5, whereas the concentration criterion (CC) was 3.25. The estimated value must satisfy the condition that the concentration criterion must be greater or equal to 2.4, i.e. ($CC \geq \pm 2.4$) for a non-ferrous ore to be susceptible to the gravity separation method [2]. The results confirm the effectiveness of both gravity separation methods in cassiterite ore beneficiation.

3.5 Chemical Composition of Magnetic and Spiral Separation Method

3.5.1 Chemical Composition of Magnetic Concentration

The weights and composition of the concentrates and tailings of Farin-Lamba cassiterite ore processed by the induced magnetic separator were determined as follows in Tables 5 and 6.

Table 5: Yield mass of Magnetic and Non-magnetic products

Sieve size (µm)	Wt of charge (g)	Wt of Magnetic (g)	Wt of Non-magnetic (g)
-500+355	1000.00	313.25	686.75
-355+250	1000.00	343.06	656.54

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-250+180	1000.00	464.76	535.24
-180+125	1000.00	300.54	699.46
-125+90	1000.00	512.73	487.27

Table 6: Chemical Analysis of Farin-Lamba Cassiterite Separated using Induced Electric Magnetic Separator

Chemical (%) composition	Magnetic separation at varying sieve sizes: 355 (µm) Conc.	355 (µm) Tailing	250 (µm) Conc.	250 (µm) Tailing	180 (µm) Conc.	180 (µm) Tailing	125 (µm) Conc.	125 (µm) Tailing	90 (µm) Conc.	90 (µm) Tailing
Al_2O_3	3.12	2.13	1.50	1.08	2.27	1.23	1.47	2.73	8.62	0.62
SiO_2	52.34	6.12	53.84	7.42	46.34	2.11	49.76	5.42	47.04	5.64
TiO_2	1.03	1.05	2.41	0.49	0.75	3.29	0.93	5.04	0.64	0.64
Fe_2O_3	6.04	60.39	6.55	61.75	3.21	64.49	6.54	59.34	6.98	54.96
ZrO_2	3.10	1.32	1.26	0.21	3.90	3.41	3.68	0.10	3.18	3.18
Nb_2O_3	1.18	1.20	1.97	0.24	1.12	3.20	2.74	0.15	1.98	1.98
SnO_2	30.42	8.01	35.13	7.45	39.42	4.24	34.39	5.04	32.63	6.86
V_2O_5	0.64	0.99	0.23	0.02	0.02	4.24	0.57	0.1	0.21	0.21
K_2O	1.02	0.96	1.64	1.05	0.75	0.90	0.86	1.12	1.61	1.61
MgO	0.58	0.68	0.31	1.18	0.98	0.47	0.62	0.32	0.93	0.93
P_2O_5	0.05	0.18	1.20	0.54	0.06	0.23	2.74	0.20	0.46	0.46

The weight of mineral deposited on magnetic and non-magnetic components fractions of an induced magnetic separation component of Farin-Lamba cassiterite at different sieve sizes for the mineral of interest (SnO_2) and the gangue minerals are shown in Table 5. There is an increase in the weight of magnetic material along sieve sizes of 355 µm (313.25 g), 250 µm (343.06 g), and 180 µm (464.76 g) and decreases at the liberation size 125 µm (300 g) with a gradual increase at sieve size of 90 µm (512.73 g). The weights of non-magnetic material, which were then subjected to spiral concentration, increased at the sieve size of 125 µm (699.46 g) and further decreased towards the sieve size of 90µm (512.73 g). This shows that the rapid magnetic separation technique was successful at distinguishing magnetic materials from non-magnetic materials. Consequently, the chemical composition of the concentrate and the tailings of the processed samples are shown in Table 6. The assay of (SnO_2) increases along sieve size 355 µm (30.42%), 250 µm (35.13%), and 180 µm (39.42%) and further decreases from sieve size 125 µm (34.39%) to 90 µm (32.63%) concentrates. Further, the assay of SnO_2 decreases along sieve size of 355 µm (8.01%), 250 µm (7.45%) and 180 µm (4.24%) and further increases from sieve size of 125 µm (5.04%) to 90 µm (6.86%) for the tailings. The sieve size 180µm had the highest assay

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of (SnO_2) at 39.42%, an improvement in the percentage assay in the crude ore from 20.22% to 39.42 %.

Table 7: Yield mass of Spiral Concentration products

Sieve size (µm)	Wt of Charge (g)	Concentrate (g)	Tailing (g)
`-500+355	500.00	80.88	419.12
-355+250	500.00	90.20	409.80
-250+180	500.00	124.84	375.16
-180+125	500.00	135.86	364.14
-125+90	500.00	153.55	346.45

Table 8: Chemical Analysis of Farin-Lamba Cassiterite Separated using Humphrey's spiral concentrator

	Spiral Concentration at varying sieve sizes									
Chemical (%)	**355 (µm)**		**250 (µm)**		**180 (µm)**		**125 (µm)**		**90 (µm)**	
composition	**Conc.**	**Tailing**	**Conc.**	**Tailing**	**Conc.**	**Tailing**	**Conc.**	**Tailing**	**Conc.**	**Tailing**
Al_2O_3	6.35	2.42	1.08	3.43	1.08	2.74	0.92	2.74	0.86	1.97
SiO_2	7.92	64.42	6.51	64.21	6.71	66.96	4.39	68.74	7.17	59.42
TiO_2	0.75	9.15	3.45	0.72	0.49	0.62	0.61	0.62	0.61	0.64
Fe_2O_3	7.01	5.61	6.49	9.10	6.32	7.42	4.84	3.93	6.82	5.59
ZrO_2	3.90	4.72	0.21	4.72	0.21	3.57	3.10	3.57	3.10	5.22
Nb_2O_3	5.42	1.60	3.24	1.60	0.24	2.50	2.00	2.50	2.20	3.05
SnO_2	54.68	4.07	55.59	4.07	63.42	4.44	73.42	2.74	54.92	7.32
V_2O_5	0.02	0.17	0.02	0.17	0.02	2.50	0.19	0.31	0.19	0.30
K_2O	0.75	1.97	1.05	1.97	1.05	1.84	1.73	1.84	0.73	2.01
MgO	0.98	1.84	0.78	1.84	1.18	0.28	1.01	0.28	0.01	0.36
P_2O_5	0.98	0.51	0.54	0.51	0.54	1.63	0.32	1.63	0.32	1.49

Results on the weight of concentrate and tailings for the Farin-Lamba Cassiterite at different sieve sizes by Humphrey's spiral concentrator revealed that the weight of concentrate material increases as the sieve size decreases. Contrary, the weight of the tailing material decreases with a decrease in the sieve size (Table 7). There was also a significant increase in the assay of (SnO_2) for the entire sieve size fractions. The chemical composition of the concentrate in the

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processed samples showed that the sieve size of 125µm has the highest assay of (SnO_2) at 73.42% as compared to other sieve sizes; this was attributed to that sieve size being the actual liberation size of the ore [8]. This shows a high improvement in the percentage concentration of (SnO_2) from 39.42%. Further, the least sieve size 90 µm had the least composition of SnO_2 which was beyond the actual economic size attributed to over-grinding of the sample [9].

Table 9: Metallurgical Accounting Parameters for Spiral Concentrator Processing

Sieve Size (µm)	Weight of Crude, F (g)	Assay of Crude, f (%)	Weight of Concentrate, C (g)	Assay of concentrate, c (%)	Enrichment Ratio (c/f)	Concentration Ratio (F/C)	Recovery (Cc/Ff) *100
355	500.00	20.22	80.88	54.68	2.70	6.18	43.74
250	500.00	20.22	90.20	55.59	2.75	5.54	49.60
180	500.00	20.22	124.84	63.42	3.14	4.01	78.31
125	500.00	20.22	135.86	73.42	3.63	3.68	98.66
90	500.00	20.22	153.55	54.92	2.72	3.26	83.41

a. Enrichment Ratio

The enrichment ratio shows the efficiency of the processing of Farim-Lamba cassiterite with the use of spiral concentration. The particle size for 125µm sieve has the highest enrichment ratio of 3.68, whereas the largest and least particle sizes of 355µm and 90µm sieves have the lowest enrichment ratios of 2.70 and 2.72, respectively. The enrichment ratio increases with a continuous decrease in the particle sizes of the mineral.

b. Concentration Ratio

The concentration ratio revealed that the spiral separation was efficient for the beneficiation of the Farin-Lamba cassiterite ore. It was observed that particle size within 355µm sieve has the highest concentration ratio of 6.18. The concentration ratio also decreases with a continuous decrease in the particle size of the mineral.

c. Recovery

It was observed that Tin oxide, with a particle size of 125µm, has the highest percentage recovery of 98.66% and at a particle size of 90µm was at a closeproximity at 83.41%. The high percentage recovery in 125µm was attributed to the low specific gravity of the grain size, which aids their separation during the fall in a sorting column. It can also be observed that the %recovery of the Farin-Lamba increases with a decrease in grain size. The grain sizes of 355µm and 250µm had low recoveries of 43.74% and 49.60%,respectively, which was not optimal. However, grain sizes of 180µm, 125µm, and

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90µm were recommended for the optimal recovery of Farin-Lamba cassiterite.

Conclusions

The research on Farin-Lamba cassiterite ore has provided insights into the physical and chemical properties of the ore and the beneficiation route of using double concentration (magnetic-spiral) towards the production of tin oxide. The following conclusions were drawn from the study:

i. Farin-Lamba cassiterite consists of tin oxide assaying 20.22% SnO_2 and other gangue minerals such as iron and silica.
ii. The specific gravity of the cassiterite was computed to be 5, and the concentration criterion was 3.25.
iii. The chemical analysis of the concentration test using induced magnetic separation revealed that 180 µm sieve size has the highest assay of 39.42% of SnO_2.
iv. The chemical analysis of the concentration test using spiral concentrator revealed that at the sieve size of 125 µm sieve composition of SnO_2 at 73.42%.
v. The concentration of Farin Lamba cassiterite using the spiral concentrator method resulted in a high grade of SnO_2 at 73.42%, translating to a recovery of 98.66%.

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Author's Contribution

AWO and EIP conducted the experimental procedure, while AOO, GF, and GYE conceptualised and designed the study, contributing to the preparation of the manuscript.

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