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Flowsheet Design of Pilot Beneficiation Plant for Melka Arba Iron and Some Essential Minerals in Ethiopia Using METSIM

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Abstract: Ethiopia possesses abundant mineral resources, including coal, iron, lithium, niobium, chromium, gold, and tantalum, yet faces challenges in efficiently utilizing these for economic development. A lack of dedicated pilot-scale beneficiation simulation flowsheets has hindered research and optimization of extraction techniques. This study proposes a common pilot beneficiation plant flowsheet using METSIM software, tested through simulation of Melka Arba iron ore magnetic separation. Equipment selection was guided by mineralogical analysis and literature review to suit Ethiopian ores, integrating industry-standard crushers, mills, and separation methods (magnetic, gravity, flotation) to streamline operations and reduce redundancy. METSIM simulations demonstrated nearly 86% magnetite recovery, validating magnetic separation's effectiveness. Mass balance confirmed successful separation of magnetite from gangue minerals. These results provide a solid foundation for process optimization, enhancing recovery, efficiency, and economic viability. The proposed pilot design offers a scalable framework to modernize Ethiopia's mineral processing industry and address the lack of standardized beneficiation approaches.

Keywords: *Flowsheet Design, METSIM Simulation Software, Common Pilot Beneficiation Plant.*

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I. INTRODUCTION

Ethiopia's mining sector holds significant promise due to its rich endowment of diverse mineral resources, including gold, tantalum, gemstones, platinum, natural gas, and industrial minerals such as quartz and marble. Supported by a strong legal framework and active government backing, the industry is positioned for rapid growth(Yihdego et al., 2018). However, the sector's mineral potential remains largely untapped, primarily due to the absence of pilot-scale processing facilities critical for research, development, and scale-up operations. These pilot plants allow for continuous, closed-circuit testing, enabling precise process optimization and reducing economic risks while enhancing the efficiency of resource utilization (Amini & Noble, 2017).

In this context, pilot plants serve as indispensable platforms for researchers, students, and industry professionals to develop and refine beneficiation flowsheets detailed blueprints that map out equipment and process sequences for efficient ore treatment. The application of simulation tools such as METSIM further accelerates this process by enabling dynamic modeling of flowsheets, identification of process bottlenecks, and digital testing of operational configurations before physical implementation(Nikkhah, 2001). This data-driven approach is critical for designing cost-effective and scalable beneficiation strategies tailored to Ethiopia's key minerals, including tantalum and gold, fostering sustainable sectoral growth.

A demonstrative application of this methodology is the beneficiation flowsheet developed and tested on the Melka Arba titaniferous magnetite deposit, located in Dolo Mena Woreda, Bale Zone of Oromia Regional State, approximately 650 km southeast of Addis Ababa and 110 km from the nearby town of Goba(Masresha, 2002). This deposit features a titaniferous magnetite orebody with sharp to gradational contacts within host rocks, composed predominantly of (45–52) % magnetite and (30–35) % ilmenite, along with minor

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amounts of chalcopyrite, pyrite, and pyrrhotite. The gangue matrix, constituting (15–25) % of the deposit, includes amphibole, plagioclase, pyroxene, and chlorite minerals. Magnetite grains, typically (0.2–0.5) mm in size, exhibit ilmenite intergrowths and fine spinel-magnetite networks, while ilmenite grains are finer, exhibiting common corrosion textures.

Chemical characterization of the Melka Arba ore demonstrates consistent composition across sampled trenches, with iron (Fe) content ranging between (48–52) %, titanium dioxide (TiO_2) at (16–19) %, low phosphorus pentoxide (P_2O_5) of (0.03–0.09) %, and sulfur levels between (0.1–0.4) %, potentially increasing at greater depths within oxidized zones. Similar assessments of dispersed pyroxenite ores at the nearby Besharo site reveal apatite concentrations of (3.36–3.92) %. Magnetic separation trials on 44 samples from Melka Arba indicate that iron grades can be enriched up to 66%, with advanced magnetic dressing techniques potentially achieving 69% Fe and 2.4% TiO_2. Grain size analysis via SEM further highlighted that 60% of apatite and 88% of ilmenite particles exceed 250 µm, with mean grain sizes of 180 µm and 230 µm respectively(Masresha, 2002).

The demonstrated beneficiation flowsheet, validated on Melka Arba iron ore, exemplifies how combining pilot-scale testing with METSIM simulation enables the optimization of mineral processing strategies tailored to local deposits, thus providing a replicable model for advancing Ethiopia's mineral sector toward sustainable industrialization.

II. METHODS

➢ *Selection of Comminution Circuit*

Selecting appropriate comminution equipment is critical for optimizing flowsheet performance, reducing operating costs, and enhancing overall plant efficiency. Equipment choices tailored to ore characteristics improve throughput, reduce energy consumption, and increase product quality, thereby maximizing profitability. Conversely, improper selection can cause operational inefficiencies and increased costs. This design prioritizes equipment that balances operational capability, cost-effectiveness, and reliability to maximize recovery and performance(Metso: Outotec, 2022).

Comminution, the fundamental stage in mineral processing, involves crushing and grinding ore to liberate valuable minerals from gangue, facilitating effective downstream beneficiation(Guldris Leon & Bengtsson, 2022). The process includes:

- *Primary Crushing (Jaw Crusher):*

Jaw crushers reduce large ore blocks into intermediate-sized particles. Adjustable gape settings allow control of particle size distribution and throughput. Recirculation of crushed material improves efficiency by minimizing the number of crushing stages(Michaud, 2016).

- *Secondary Crushing (Cone Crusher):*

Cone crushers perform intermediate and tertiary crushing by compressive breakage between a fixed outer cone and a moving inner cone. They process material from the jaw crusher in a closed circuit, producing material with a P80 below 10 mm, optimizing circuit efficiency and minimizing the number of stages(Guldris Leon & Bengtsson, 2022).

- *Grinding (Ball Mill):*

Grinding reduces particles to finer sizes between 5 to 20 mm to liberate minerals and increase surface area for separation. Ball mills pulverize material to sizes suitable for separation techniques such as flotation, gravity, or magnetic methods(Balasubramanian, 2017).

- *Hydrocyclone Classification:*

Hydrocyclone continuously classify slurry using centrifugal force to separate fine undersized particles from coarse oversize material(Dodo et al., 2024). Oversized particles are recycled to the mill for further grinding, ensuring optimal particle size distribution and process efficiency. Hydrocyclone operate effectively at typical slurry solids concentrations and serve versatile roles including classification, de-sliming, and thickening(Hore & Das, 2011).

➢ *Selection of Mineral Separation Method*

Choosing the appropriate mineral separation methods is essential for maximizing recovery from Ethiopia's complex and diverse ores. For this pilot plant design, three primary beneficiation techniques were selected: magnetic separation, gravity separation, and flotation.

- *Magnetic Separation:*

Especially effective for Ethiopian iron ores such as magnetite and hematite, magnetic separation consistently achieves iron recoveries greater than 80%, producing high-grade concentrates. Its efficiency is optimized by controlling feed particle size and magnetic field strength. The method is cost-effective, requires minimal maintenance, and is well suited for pilot-scale operations(Bryson, 2004; Meseret et al., 2025).

- *Gravity Separation:*

Utilizing jigs and pulsating water currents, gravity separation exploits differences in mineral densities to recover dense minerals such as gold, iron, and tantalum down to particle sizes of approximately 75 µm. Jigs are robust, chemical-free, environmentally friendly, and capable of handling wide size ranges (3–10 mm), making them highly adaptable for pilot plant-scale beneficiation. Their proven industrial performance further validates their selection (Bryson, 2004; Meseret et al., 2025).

- *Flotation:*

Flotation separates minerals based on differences in surface chemistry, excelling in processing complex, fine-grained ores that are challenging for magnetic or gravity separation. By selectively attaching hydrophobic mineral particles to air bubbles, flotation improves recovery and concentrate purity, especially for ores containing impurities

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like silica and ash. Its reagent adjustability and (Keshav, 2013).

Together, these methods form an integrated and flexible toolkit for the pilot plant, enabling efficient and selective recovery of valuable minerals across a broad spectrum of Ethiopian ore types.

➢ *Separation of Melka Arba Iron Ore Using Magnetic Separator in METSIM*

The separation of Melka Arba iron ore using METSIM focused on validating the pilot plant flowsheet through magnetic separation. Effective comminution was essential, as most ilmenite and apatite grains exceeded 250 µm, requiring careful crushing and grinding to achieve optimal liberation while minimizing fines. Given the ore's high magnetite content (45–52%), magnetic separation was the preferred method, capable of producing concentrates up to 66% Fe, with potential for higher grades using advanced techniques. Gravity separation was less suitable due to similar mineral densities, and flotation was reserved for sulfide and ilmenite recovery. Overall, the METSIM simulation confirmed that a flowsheet centered on magnetic separation potentially followed by flotation offers an efficient and scalable solution for maximizing iron recovery and by-product value from Melka Arba ore.

➢ *Data Setup and Process Design in METSIM*

The powerful software METSIM might be used to model and simulate any known inorganic and metallurgical chemical processes. METSIM is used by companies worldwide to plan, simulate, and oversee a wide range of operations, from tailing to mining and all in between (Isbn, 2014). The first step in using METSIM is to register the project name and to set different general parameters. Users then input all of the identified minerals from the test samples into the mineral dialog box (figure 1), which provides an accurate depiction of the ore's composition for precise process simulation.

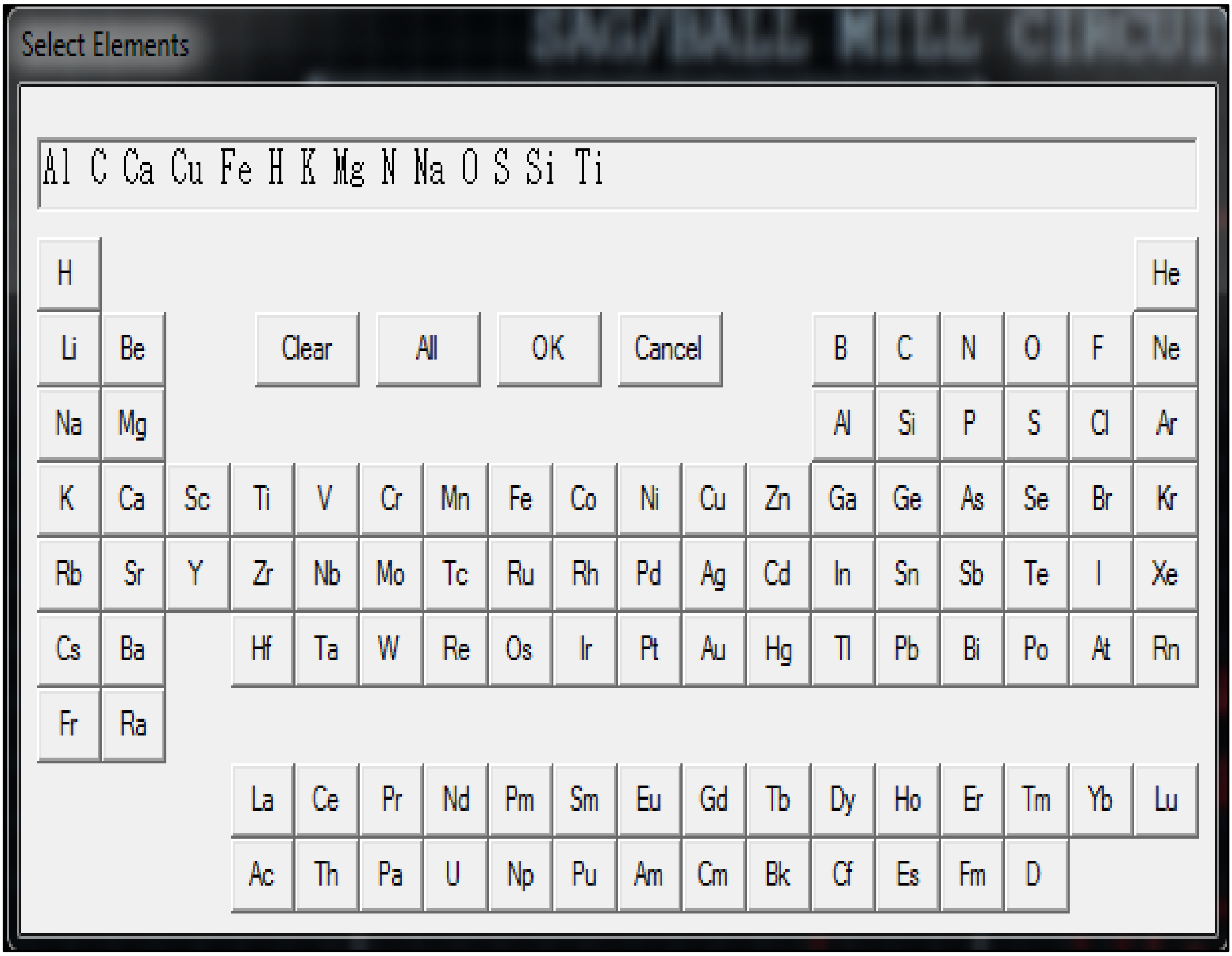

Fig 1 Overview of Elements Incorporated in METSIM Simulation

Then METSIM produced a large number of compounds from the input minerals. Then the essential molecules which are found on Melka Arba iron were chosen for simulation (figure 2). This choice guarantees that the simulation model accurately captures the mineralogical complexity of the ore.

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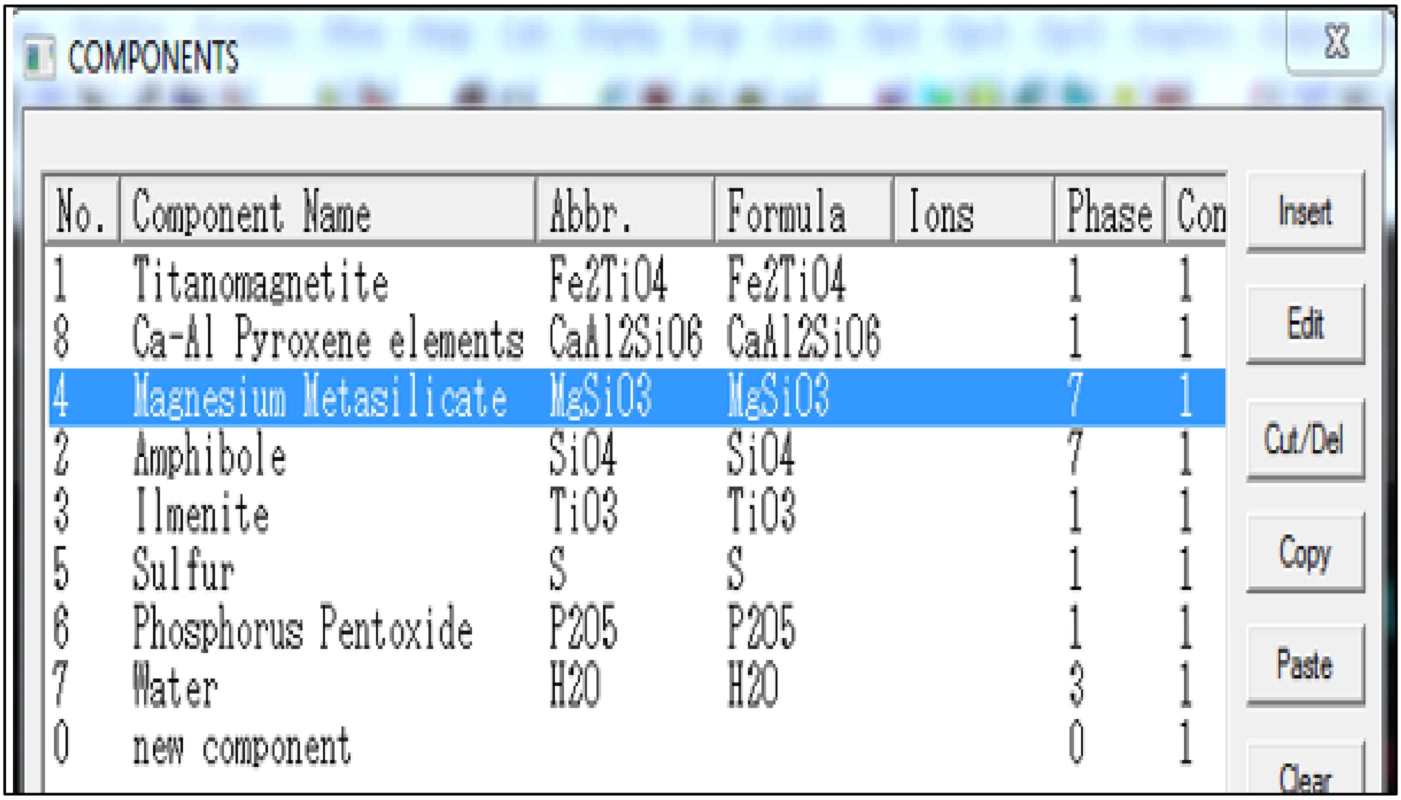

Fig 2 Key Components for METSIM Simulation of Melka Arba Iron Beneficiation

The researcher input the fraction of each compound and element from the laboratory mineralogical data of Melka Arba Iron into the METSIM simulation software. METSIM then provided the elemental fraction distribution of the feed materials (Figure 3).

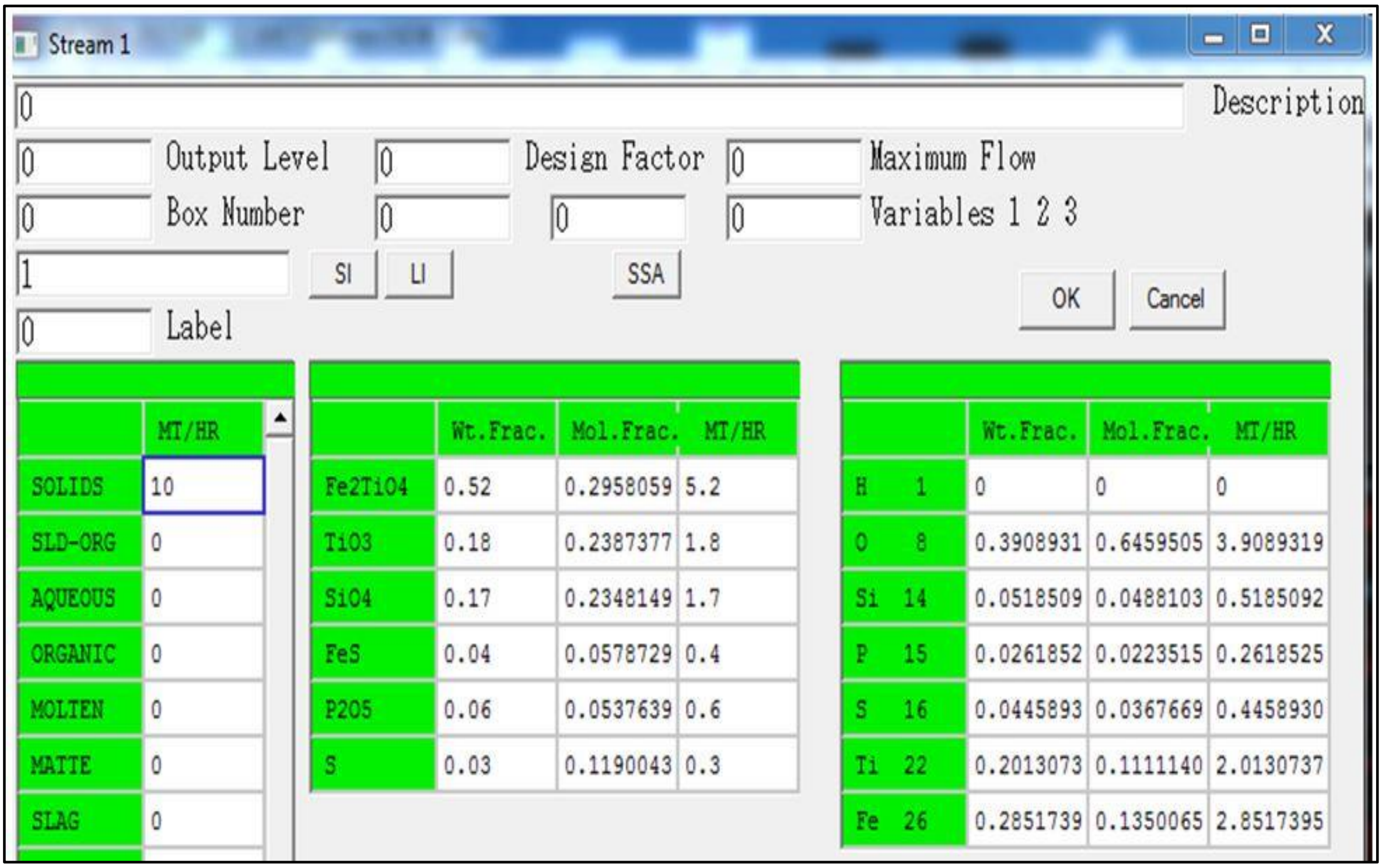

Fig 3 Weight Fraction of Compounds and Elements in Melka Arba Iron Ore from METSIM Data

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III. RESULT AND DISCUSSION

➤ *Comminution Circuit Optimization*

The crushing circuit employs a jaw crusher and a cone crusher as primary and secondary crushers, respectively. These operate in a closed circuit with a two-deck inclined screen, eliminating the need for a tertiary crusher. The grinding circuit consists of a single ball mill. The combination of the ball mill and hydrocyclone in a closed circuit facilitates fine grinding, with larger particles recycled for further processing. The screening process is streamlined using a two-deck inclined screen that serves the jaw crusher, cone crusher, and ball mill. A secondary belt conveyor transports the crushing circuit's output to the grinding circuit, while a single belt conveyor recycles the jaw and cone crushers' output back to the screen for re-grinding.

➤ *Flexible Separation Flowsheet*

Various separation techniques can be applied in parallel or in series using a stream splitter to optimize mineral processing. In a parallel circuit, hydrocyclone overflow passes through a magnetic separator, separating magnetic and non-magnetic minerals directly, with flexibility to switch to flotation or gravity separation. In a series circuit, magnetic separation precedes gravity separation, with products potentially reground and floated for further concentration. The stream splitter allows rerouting flows between magnetic, gravity, and flotation stages based on performance metrics. This flexible flowsheet combines efficient comminution with adaptable separation techniques, enabling tailored processing for diverse Ethiopian mineral deposits.

➤ *Particle Size Distribution Analysis of Comminution Method*

Particle size distribution (PSD) analysis is critical in comminution circuits due to its direct influence on process efficiency, mineral liberation, and the performance of downstream separation techniques. Proper understanding of PSD enables operators to minimize energy consumption, avoid over-grinding, and reduce operational costs. Additionally, precise PSD measurement helps define optimal conditions for mineral liberation, ensuring effective extraction of valuable minerals from gangue (Terzi, 2018). PSD data is essential for designing and optimizing downstream processes such as magnetic, gravity, and flotation separation because particle size significantly impacts recovery and product quality.

The jaw crusher processes the iron ore overflow (80% passing 181 mm) from the two-deck inclined screen efficiently, reducing the feed size from an F80 of 161,211 µm to a P80 of 33,863 µm passing a 45 mm screen (figure 4). Jaw crushers operating in a closed circuit with cone crushers and screens generally exhibit reduction ratios between 4:1 and 8:1(Fuzhen, 2024).

$$\text{Reduction Ratio (RR)} = \frac{161{,}211\ \mu m}{33863\ \mu m} = 4.75$$

This reduction ratio (RR) is a key indicator of jaw crusher efficiency, describing the crusher's ability to decrease feed size to the desired product size.

The target PSD was achieved by iteratively adjusting the cone crusher’s open and closed side settings using METSIM simulations. Specifically, 80% of the feed from the Cone crusher passes through a 45 mm screen with an F80 of 37,967 µm and a P80 of 10,013 µm through an 11 mm screen, aligning with optimal feed parameters for efficient ball mill operation (figure 4). The cone crusher’s reduction ratio typically ranges between 3:1 and 5:1, or higher (Michaud, 2016).

$$\text{Reduction Ratio (RR)} = \frac{37{,}967\ \mu m}{10013\ \mu m} = 3.79$$

The reduction ratio confirms the cone crusher’s excellent comminution efficiency. Maintaining and improving this performance through METSIM simulations of critical parameters such as open and closed side settings ensures consistent and reliable size reduction.

Solids screen analysis showed that an 11 mm screen with an F80 of 8949 µm filtered 80% of the ball mill feed. The ball mill product obtained a P80 of 1263 µm after grinding and classification by hydrocyclone, indicating 80% of the material passing through a 1 mm screen (figure 4). This particle size distribution is suitable for subsequent processing and illustrates efficient size reduction. Standard reduction ratios for ball mills are generally between 5:1 and 20:1 for open-circuit grinding, but closed-circuit grinding often requires ratios below 10:1 (MLANDVO BRIAN THEMBINKOSI DLAMINI 2019). Achieving such reduction ratios is vital for optimal mineral liberation and downstream processing.

$$\text{Reduction Ratio (RR)} = \frac{8949\ \mu m}{1263\ \mu m} = 7.1$$

The ball mill's high comminution efficiency is evidenced by this reduction ratio, which can be further optimized by precisely controlling feed size, ball charge, and mill speed using METSIM.

➤ *Magnetic Separation of Melka Araba Iron*

Magnetic separation is a critical beneficiation technique for iron ores such as the Melka Araba deposit in Ethiopia. This method effectively separates iron minerals from non-magnetic gangue by exploiting magnetic properties of minerals like magnetite and other magnetic materials, which have strong magnetic responses(Xiong et al., 2015). The process depends heavily on adequate liberation of iron-bearing minerals through comminution.

Grinding and crushing operations liberate magnetic particles from gangue, a prerequisite for efficient magnetic separation. The degree of liberation directly affects separation performance, improving concentrate quality and overall recovery. Therefore, optimizing the comminution circuit before magnetic separation enhances recovery rates and produces a cleaner, higher-grade iron ore concentrate

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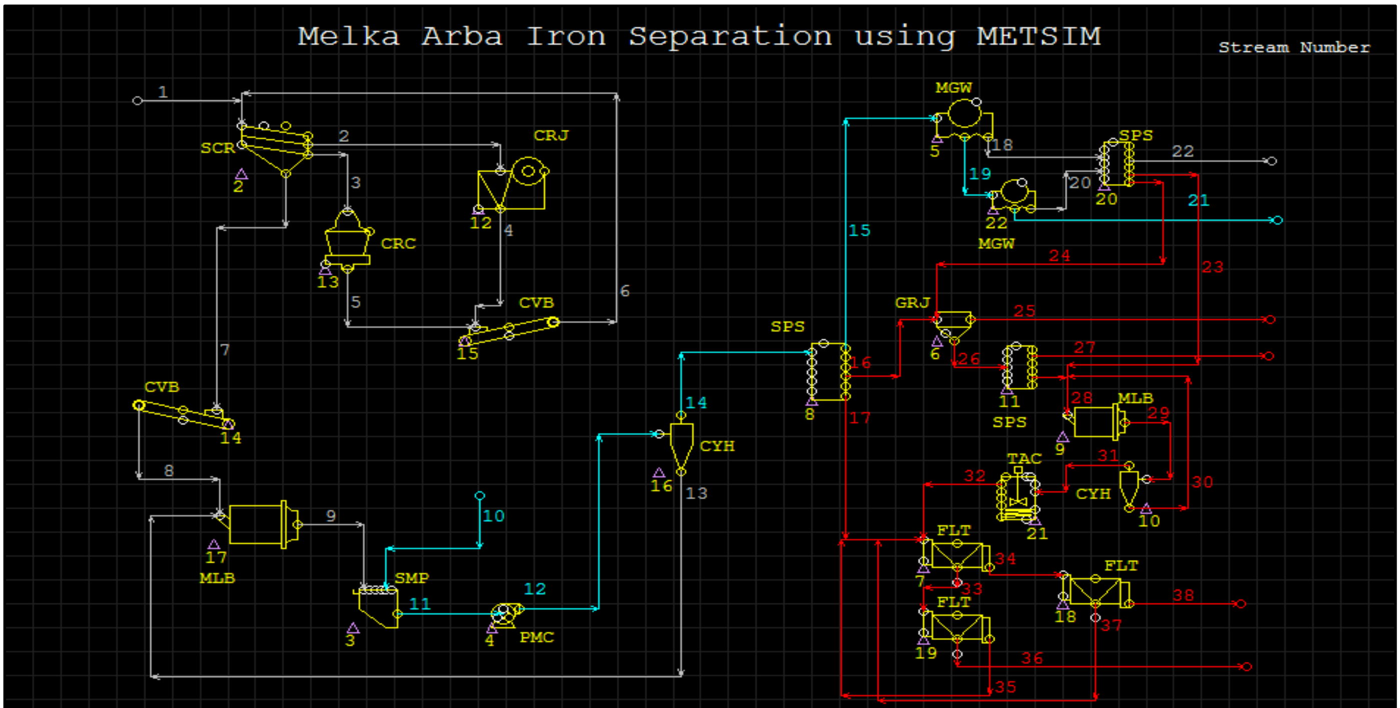
suitable for direct use or further processing(Xiong et al., 2015).

Identifying the appropriate P80 enables targeted grinding and separation strategies that maximize magnetite recovery while minimizing energy consumption and processing costs. The following figure illustrates the spreadsheet table and general flow streams that simulated Melka Araba iron ore separation based on a specific particle size distribution.



Stream	2	3	4	5	6	7	9	12	13	14	15	18	19	20	21	22
Solids tph	5.350	5.157	5.350	5.157	10.51	10.00	36.74	36.74	26.74	10	10	4.472	5.528	0.520	5.008	4.992
% Solids	100	100	100	100	100	100	61.56	32.47	53.73	13.06	13.06	75	20.66	60	19.34	73.10
P80	160887	37967	33863	10013	23378	8949	1263	1263	1473	199.9	199.9	199.9	199.9	199.9	199.9	199.9

Fig 4 Magnetic Separation Simulation of Melka Arba Iron at 199.9 µm PSD

➢ *Effect of Particle Size Distribution (PSD) in Separation Method*

Optimal magnetite recovery is achieved at a P80 of approximately 200 µm, within the particle size distribution (PSD) range of 150–250 µm, as demonstrated by the METSIM flowsheet (Figure 4). When the P80 exceeds 250 µm, coarse particles impede effective magnetite liberation, leading to a decline in recovery. Conversely, a P80 below 150 µm generates excessive fines (slimes), which exhibit poor magnetic separation behavior and contribute to increased losses. Therefore, both excessively coarse and excessively fine particle sizes adversely affect magnetite recovery, underscoring the critical importance of maintaining a P80 near 200 µm to maximize separation efficiency.

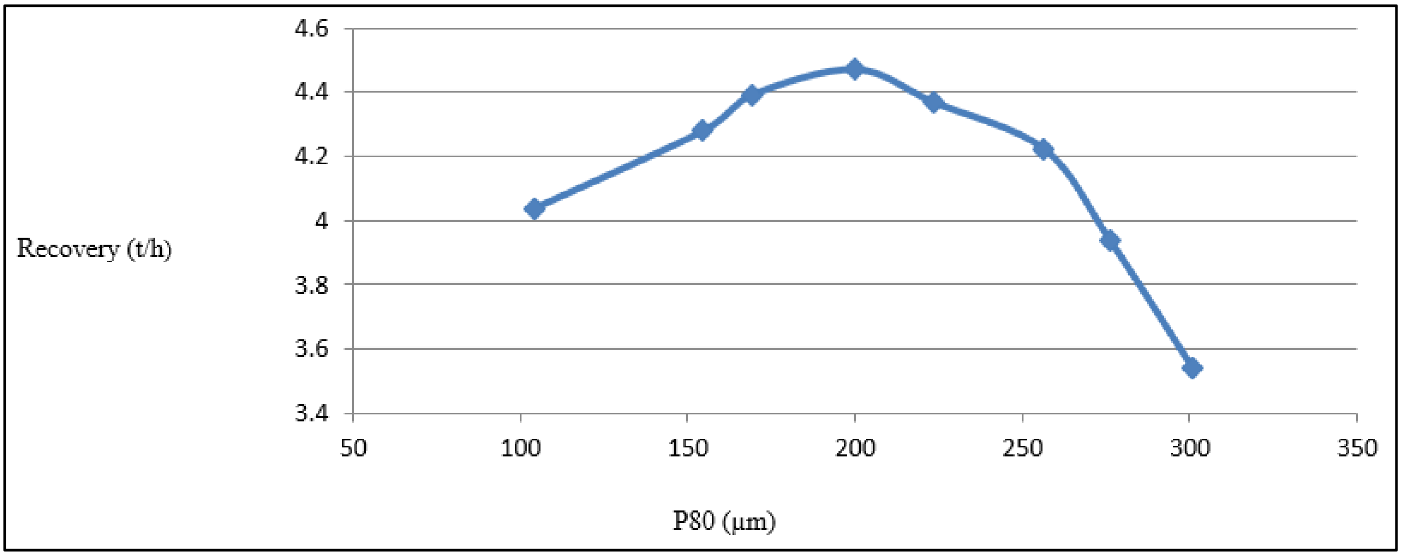


Fig 5 Relationship Between P80 Particle Size and Magnetite Recovery

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➢ *Recovery*

Important insights into the effectiveness of magnetic separation for isolating magnetite from accessory and gangue minerals are provided by the METSIM simulation of Melka Arba magnetite ore. The key results are summarized as follows:

- *Initial Feed Conditions and Composition:*

The feed ore consists of 52% magnetite and 48% gangue and accessory minerals. The simulation was conducted with a feed rate of 10 t/h.

- *Simulation Results:*

Magnetite recovery amounted to 4.472 t/h from the 10 t/h feed. Ilmenite recovery was 0.52 t/h (see Figure 3 or Figure 4). The residual, comprising non-magnetic gangue and accessory minerals, accounted for 5.008 t/h (Figure 3).

- *Mass Balance Verification:*

Mass balance is validated by the equality between the total feed (10 t/h) and the sum of recovered magnetite and ilmenite (4.992 t/h) plus gangue and accessory minerals (5.008 t/h).

- *Recovery Efficiency:*

The magnetite recovery percentage can be calculated to evaluate process performance. The initial magnetite mass in the feed is:

$$= 10\ t/h \times 0.52 = 5.2 t/h$$

According to the METSIM concentration stream dialog (Figure 6), titaniferous magnetite contains 4.472 t/h in total iron concentrate, with 2.234 t/h of iron content. Additionally, the magnetite concentrate includes 1.1 t/h of tin. This tin concentration exceeds the amount required to improve iron properties. Therefore, further beneficiation methods such as flotation or alternative metallurgical techniques should be explored using METSIM to optimize recovery and concentrate quality.

➢ *Magnetite Recovery in Concentrate*

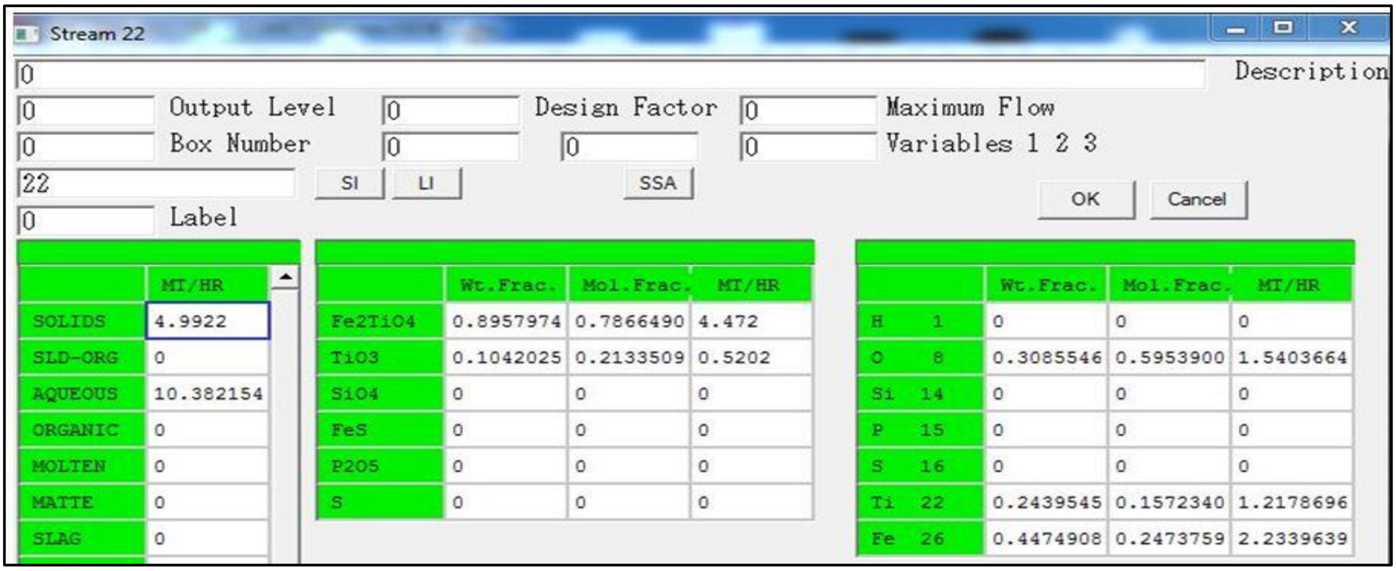
$$R_{Magnetite} = \frac{\text{Mass of Magnetite Recovered}}{\text{Initial Mass of Magnetite in Feed}} \times 100\% = \frac{4.472\ t/h}{5.2\ t/h} \times 100\% = 86\ \%$$

The results indicate that approximately 86% of the magnetite in the feed was successfully recovered. The beneficiation simulation of Melka Arba iron ore using METSIM software provides valuable insights into the efficiency of magnetic separation for isolating magnetite from accessory and gangue minerals.

➢ *Iron Recovery in Concentrate:*

The original iron mass is 2.852t/h (Figure 1), and the recovered iron is 2.234t/h (Figure 21). Therefore:

$$R_{Fe} = \frac{\text{Mass of Iron Recovered}}{\text{Initial Mass of Iron in the ore}} \times 100\% = \frac{2.234\ t/h}{2.852\ t/h} \times 100\% = 78.33\ \%$$



	MT/HR
SOLIDS	4.9922
SLD-ORG	0
AQUEOUS	10.382154
ORGANIC	0
MOLTEN	0
MATTE	0
SLAG	0

	Wt.Frac.	Mol.Frac.	MT/HR
Fe2TiO4	0.8957974	0.7866490	4.472
TiO3	0.1042025	0.2133509	0.5202
SiO4	0	0	0
FeS	0	0	0
P2O5	0	0	0
S	0	0	0

	Wt.Frac.	Mol.Frac.	MT/HR
H 1	0	0	0
O 8	0.3085546	0.5953900	1.5403664
Si 14	0	0	0
P 15	0	0	0
S 16	0	0	0
Ti 22	0.2439545	0.1572340	1.2178696
Fe 26	0.4474908	0.2473759	2.2339639

Fig 6 Magnetite and Element Concentration Results from METSIM

➢ *Grade*

The percentage of recovered magnetite in relation to the total input mass determines the magnetite grade:

$$\text{Magnetite Grade} = \frac{\text{Recovered Magnetite}}{\text{Feed Rate}} \times 100\% = \frac{4.472\ t/h}{10\ t/h} \times 100\% = 44.72\ \%$$

The iron grade in the concentrate is as follows, based on the METSIM modeling conclusion that the ore contains 49.96% iron:

$$\text{Fe \% in Magnetite} = \frac{\text{Recovered Iron}}{\text{Recoverd Magnetite}} \times 100\% = \frac{2.234\ t/h}{4.992\ t/h} \times 100\% = 49.95\ \%$$

$$\text{Iron Grade} = \text{Magnetite Grade} \times \text{Fe \% in Magnetite} = 44.72\ \% \times 49.955\ \% = 22.34\ \%$$

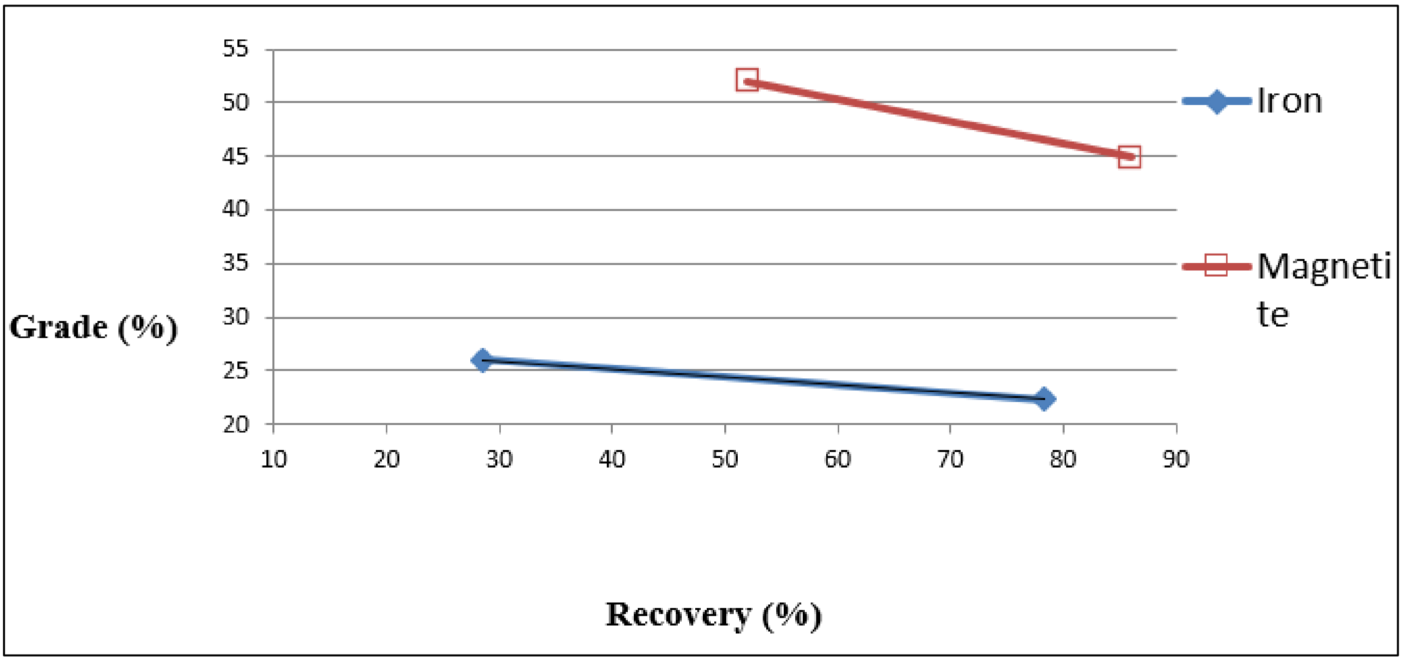


Fig 7 Recovery Versus Grade Performance Curve

Just over half of the feed mass is recovered as magnetite concentrate with a grade of 44.72%. Assuming magnetite contains 44.75% iron, the concentrate's iron grade is approximately 22.23%, representing its actual iron content a critical factor for product quality and profitability. Despite the substantial magnetite content in the concentrate, the relatively moderate iron grade indicates that additional upgrading or beneficiation may be required to meet processing or market specifications for total iron content. In summary, magnetite recovery is satisfactory, but improving the iron grade through beneficiation adjustments is necessary. Enhancing the iron grade will increase the concentrate's market value and improve its efficiency in steelmaking. Further research into advanced separation methods is recommended to achieve higher grades and optimize overall performance.

IV. CONCLUSION

The research successfully developed and validated a pilot-scale beneficiation plant flowsheet for Melka Arba iron ore using METSIM simulation software. The optimized comminution circuit comprising jaw and cone crushers with a ball mill achieved efficient particle size reduction conducive to mineral liberation. Magnetic separation demonstrated a magnetite recovery of approximately 86%, confirming its effectiveness as the primary separation technique. The mass balance results verified the successful concentration of magnetite, reducing gangue minerals. The integration of gravity and flotation methods offers additional flexibility for processing accessory minerals. These findings establish a scalable framework to enhance mineral recovery, operational efficiency, and economic viability, addressing the lack of standardized beneficiation processes in Ethiopia. This pilot design provides a practical foundation for further process optimization and sector modernization.

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➢ *Ethics Approved and Consent to Participate*
Not applicable

➢ *Consent for Publication*
Not applicable

➢ *CRedT authorship Contribution Statement*

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➢ *Declaration of Competing Interest*

The authors declare the following financial interests/personal relationship which may be considered as potential competing interest: Addis Ababa University supports for some financial for thesis preparation, and Ethiopian Ministry of Mines supports the master's scholarship.

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