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UPGRADING THE IRON GRADE OF BIKILAL IRON ORE USING MAGNETIC SEPARATION METHOD WITH FRANTZ LABORATORY MAGNETIC SEPARATION

2023, June

DEGAGA AMENU HAMBISA

A Project work Submitted to Center for Ethio-mines development in partial fulfillment of the requirements for the degree of Master of Engineering in Mineral Engineering.

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This is to certify that the project work prepared by Degaga Amenu, entitled: Upgrading the Iron Grade of Bikilal Iron Ore by Magnetic Separation Method with Frantz Laboratory Magnetic Separation, submitted in partial fulfillment of the requirement for the degree of Master of Engineering in Mineral Engineering, complies with the regulation of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining Comittee:	**Signature**	**Date**
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DECLARATION

I hereby declare that the research project entitled upgrading the iron grade of Bikilal iron ore by magnetic separation method with Frantz laboratory magnetic separation is my original work and that I have not copied or plagiarized from other source. I also state that I have obeyed to the ethical principles and standards required for conducting this research. I have acknowledged all the sources of information and papers that I have used in this project work. The work was under the guidance of Dr. Dejene Hailemariam, the general director of the Geological Institute Ethiopia, and Mr. Wondefrash Mamo, a senior geologist at the Geological Institute Ethiopian.

Degaga Amenu …………………..   ………………………

Signature   Date

ABSTRACT

The iron ore deposit of the Western Oromia Region of Ethiopia, at Bikilal, is a huge deposit, but it is low in grade. It assays 19.50 % Fe_2O_3 and 45.66% SiO_2. The present study is an attempt to investigate the potential of this ore for upgrading at laboratory scale. Based on the appreciable differences in magnetic susceptibility between the desired iron minerals and gangue minerals, it was suggested that magnetic separation may be useful to concentrate this type of iron ore. The study used two feed size fractions (-500+75 micrometers; -300+75micrometers) and two currents 0.4 ampere; 0.8 ampere), and performed four experiments by adjusting these operating factors.

The iron grade and recovery were measured and recorded for each combination of tests. For run 1and 2, that received -500+75µm and 0.8 and 0.4 ampere respectively, the results of iron grade and recovery, in % were 25.02; 83.73% and 20.84;68.63%. For run 3 and 4, that received -300+75µm and 0.8 and 0.4ampere, the obtained iron grade and recovery were 31.18;90.17 % and 26.64;75.63%. Factorial Design, particularly, Two Level Factorial Design was applied to investigate the effects of feed size (-500+75 and -300+75µm) and current (0.4 and 0.8 ampere) on the process of Frantz laboratory magnetic separator using Design expert v13 software, which shows the significant influence on the values of Fe grade and recovery at roughing stage of the concentrate. The results showed that both feed size and current had a significant effect on the iron grade and recovery, and their interaction had not significant. The optimal condition was found to be using a feed size fraction of -300+75 micrometer and a current of 0.8 ampere, which gave an iron grade of 31.2 % and an iron recovery of 90.2 %.

The study demonstrated that the Frantz® Low Field Control Model LFC-2 is a useful accessory for separating ferromagnetic materials according to differences in their magnetic properties. The study also provided some insights into the trends and correlation among the factors and responses, which can help to understand and optimize the magnetic separation process.

Key words: Bikilal iron ore, Upgrading, Fe grade, Magnetic separation, Frantz magnetic separation

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Lastly, I would like to dedicate this work to my family for their unyielding support, encouragement, and understanding. Your belief in me has been a driving force behind my accomplishments.

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ACCRONYMS

AAS: Atomic absorption spectrometry

%Fe: Percentage of Metal iron

FMLS: Frantz laboratory magnetic separation

LFC: Low Field Control

µm: Micrometer

A: Ampere

CGE: Central Geological laboratory

HIMS: High intensity magnetic separator

GSI: Geological Survey Institute

LIMS: Low intensity magnetic separator

ANOVA: Analysis of variance

IOA: Iron oxide apatite

REE: Rare Earth Element

Mags: Magnetic product

AAiT: Addis Ababa Institute of Technology

CHAPTER ONE: INTRODUCTION

1.1.BACKGROUND

Iron ore is one of the most important mineral resources in Ethiopia, with an estimated reserve of 600 million tons (GSE). However, most iron ore resources have low iron content and need to be processed to produce high-quality iron ore concentrates. The quality of iron ore is typically measured by its iron grade. The grade for iron ores used in blast furnace operation, which is the most common route for iron making, is around 64–65% (Roy, 2020). However, many iron ores contain impurities such as silica, alumina, and phosphorus, which lesser the iron grade and make it undesirable for steelmaking. Therefore, upgrading/enriching the low- grade iron ore by using physical means is essential in order to meet the demand for high-quality iron ore.

The generally used method for improving low-grade iron ores is magnetic separation and flotation (Roy, 2020). Magnetic separation is operators's choice over flotation, as it can separate iron bearing-minerals from gangue minerals based on their different magnetic susceptibilities (Flippov, 2014).

Bikilal iron ore deposits in western Ethiopia is one of the largest in the country, but it has a low iron grade with an average grade of 23.29 % iron (Fe). Previos studies have shown that Bikilal iron ore can be improved by using a shaking table followed by a wet low-intensity magnetic separator to separate the iron minerals from the gangue. However, these advanced technologies are too expensive and complex for small-scale applications. Therefore, this research project aims to explore the feasibility of using a Frantz laboratory magnetic separator, which is a simple and low-cost device, to upgrade Bikilal iron ore.

The Frantz laboratory magnetic separator consists of a chute with an electromagnet at one end and a splitter at the other end. The chute can be tilted at different angles to control the feed rate and slope of the magnetic field. The electromagnet can be adjusted to vary the current and the intensity of the magnetic field. The splitter can be moved to separate the magnetic fraction from the non-magnetic fraction.

Numerous factors affect how particles separate in a magnetic field. Applied current and feed size are two of the key elements that influence how well a magnetic separator performs. The amount of iron values that are liberated from the unwanted minerals depends on the feed size. It also affects how quickly the particles settle in a magnetic field and how susceptible they are to it. Current determines the strength and gradient of the magnetic field, which affect the force on the particles and their trajectories in the chute.

In the present investigation, Frantz laboratory magnetic separation of low-grade Bikilal iron ore containing 19% Fe_2O_3 has been studied using a 2x2 factorial design. The effect of process variables on magnetic separation has been analyzed using a statistical tools to describe the relationships between the factors and responses.

1.2. STATEMENT OF THE PROBLEM

Bikilal iron ore is located in the Western Part of Ethiopia in West Wollega Zone (Rebso, S. 2013). It is a Kiruna-type magnetite-ilmenite deposit that is formed by magmatic processes within a gabbroic intrusion (Rebso, S. 2013). Bikilal iron ore has a low-grade with an average of 23.3% magnetic iron and 41% total iron (Abera, 2005). In iron ore of magmatic origin, the iron oxide mineral typically makes up most of the ore and is the primary source of iron. Magnetite is the most prevalent iron oxide mineral, but hematite can also be present. Unlike high grade iron ore deposits which require simple beneficiation to produce high grade iron ores, magnetite ores require extensive beneficiation to produce the grade for iron ores used in the blast furnace operation, which is the common route for iron making. The main reason why magnetite ores need extensive processing to produce high quality iron ore products is that they are fine grained and complex in mineralogy, requiring fine and ultrafine milling (usually finer than 45µm) to separate the magnetite mineral from the predominantly silica gangue (Baawuah et al., 2020). Further, iron ore of magmatic origin is mostly diluted by phosphorous, a contaminant that can be hard to remove, from co-crystallizing apatite. Its presence in the ore poses significant challenges for its economic extraction and utilization.

In many plants around the world, low-grade iron ores have been processed successfully through magnetic separation techniques alone or in combination with other physical or chemical separation methods to reduce the level of impurities in the ore. The Bikilal iron ore deposit was discovered in the early 1988's by phase II activities of Ethio-Korean Iron Ore Exploration Project. However, amenability of the ore to be beneficiated by magnetic separation process alone or in combination with other separation techniques using proposed magnetic separation techniques in this present work has not been investigated. Samples from the iron ore deposit at Bikilal area will be characterized first mineralogically and chemically to establish a basis for beneficiation study. According to the literature different particles present in the iron ore possess different magnetic properties by which magnetic separator exploits those properties to separate them from one another. For example, magnetite, which has very high magnetic susceptibility (1000-2000 gauss) uses magnetic separators for its concentration (Iron, n.d.; Iron Ore and Its Beneficiation Potential, n.d.; Xiong et al., 2015). Based on this fact, magnetic separators will be suggested to enhance the ores quality and value of Bikilal iron ore deposits. However, the magnetic separation performance depends on various factors. Feed size fraction and magnetic field intensity are important among them. Therefore, it is essential to investigate these factors and optimize them for achieving the best results.

1.3. OBJECTIVES

1.3.1. General objective.

The general objective of this project was to investigate the potential of Bikilal iron ore, Western Ethiopia, for upgrading by magnetic separation method with Frantz Laboratory Magnetic Separator Model LFC-2.

1.3.2. Specific objective.

The specific objectives were:

- To review previous studies on the mineralogy of Bikilal iron ore deposits to identify mineral phases present in the ore.
- To characterize the Bikilal iron ore sample in terms of its chemistry.
- To conduct a beneficiation test using a Frantz Laboratory Magnetic Separator.
- To investigate the effects of particle size and magnetic field intensity on the effectiveness of the Frantz laboratory magnetic separator.

1.4. RESEARCH QUESTIONS

- Does the Frantz laboratory magnetic separation potentially suitable for upgrading Bikilal iron ore?
- How do feed size fraction and current affect the Frantz magnetic separation performance?

1.5. SIGNIFICANCE OF THE PROJECT

Ethiopia's demand and supply for steel, which may aid in industrialization and the country's economy, are seriously out of balance. This imbalance presents the domestic steel industry with both a challenge and a chance for growth. However, the importation of semi-finished and finished steel products, which consumes a lot of foreign currency, is the main source of revenue for the local steel sector. Additionally, because they are expensive and insufficient locally, scrap metal and imported billets are used for the majority of local steel manufacturing (IPSRD & ASTU, 2015-2025). Therefore, there is a need to utilize the abundant iron ore resources in Ethiopia, which can provide a sustainable and competitive source of raw material for the domestic steel industry.

Bikilal iron ore is a significant mineral resource in Ethiopia, as it is one of the huge iron ore deposits in the country, with an estimated reserve of 57.8 million tons. It has a low grade, but it can be upgraded by magnetic separation using a Frantz laboratory magnetic separator, which is simple and low cost device. The upgraded iron ore can be used for steel production, which is an important industry for Ethiopia’s economic development.

Bikilal iron ore is also a kiruna-type magnetite-ilmenite deposit which is rare and valuable in the world. Kiruna type deposits are associated with magmatic intrusions and have high phosphate resources that has promising concentrations of phosphorus element, which can be used as raw material for phosphorous based fertilizer production in Ethiopia that can enhance the agricultural productivity in the country.

Therefore, this project is of great importance as it provides the first beneficiation report of the Bikilal iron ore deposit, which is not only a source of iron but also a potential source of other strategic metals that can be upgraded by magnetic separation technique alone. The results of this project provide a basis for further investigation and development of the Bikilal iron ore deposit, which can contribute to the growth and competitiveness of this domestic steel industry.

1.6. SCOPE OF THE STUDY

The scope of this project generally limited to the use of the Frantz Magnetic Separator used in conjunction with Low Field Control Model LFC-2 for the magnetic separation process. The study used two feed size fractions (-500+75 µm and -300+75 µm) and two currents (0.4 and 0.8 ampere) as factors, and performed four experiments by adjusting these factors. The study measures and calculates the iron grade and recovery for each experiment, and analyzes the data using ANOVA. The study does not consider other factors that may influence the magnetic separation performance, such as magnetic field distribution, particle shape and density, or magnetic susceptibility.

1.7. LIMITATION OF THE STUDY

The study has some limitations that should be acknowledged. These limitations can be grouped in to four categories: sampling, experimental, analytical and practical limitations.

- **Sampling limitations:**
    - The study used a small sample size of four experiments, which may not be representative of the whole population of Bikilal iron ore.
    - The ore samples were not representative of the whole population of Bikilal iron ore, as they were collected from a limited area store. This may introduce sampling bias and reduce the generalizability of the results.
- **Experimental limitations:**
    - The study considered two levels of feed size fraction and current, which may not capture the full range of variation in these factors.

  - The study did not measure or control other factors that may influence the magnetic separation performance, such as magnetic field distribution, particle shape and density, or magnetic susceptibility.

  - The only laboratory magnetic separator available was the Frantz Magnetic Laboratory Separator, which may not be the most suitable or efficient device for separating the Bikilal iron ore. Other types of magnetic separators, such as wet low-intensity David tube drum magnetic separators or dry drum are more preferable than Frantz, and may offer better results for upgrading the iron grade of the Bikilal iron ore type.

- **Analytical limitations:**

  - The ore samples were not fresh, as they were exposed to oxidation for a long time. This may alter chemical composition of the ore and affect the magnetic separation performance.

  - The ore samples were small in size, which may not be sufficient to obtain reliable and representative results. This may also increase the experimental error and uncertainty.

  - The laboratory technician had no idea about the mineralogy of the ore and how the FMLS works, which may compromise the quality and validity of the experimental procedure and data.

These limitations suggest some directions for future research, which are discussed in the recommendation section.

CHAPTER TWO: REVIEW OF LITERATURE

2.1. INTRODUCTION

World crude steel production has consistently risen and reached a record high of 1.951 billion tons in 2021, as depicted in Figure 2.1 (Worldsteel, 2022). The global consumption trends of crude steel have also increased, with demand for iron ore rising in the iron and steel sector. According to Steel and Raw Materials, 2021, iron ore production grew to 2.3384 billion tons in 2020, leading to a significant increase in demand for this commodity.

The decline in the grade of iron ore deposits due to extensive mining has led to challenges in recovering high iron content ore through conventional screening methods. Blast furnaces remain the primary source of iron production. However, if low-grade ore is charged without further processing, it would result in significantly reduced production and increased energy consumption. Direct reduction furnaces also require high-iron-grade raw materials. Therefore, upgrading ore through physical separation technology has become an essential step in the raw material processing stage. Several operating mines have already adopted this method, and several existing mines have used it to upgrade their ore.

Rocks and minerals are classified as iron ores if they contain metallic iron that can be economically extracted. One particular mineral grouping, known as the "Kiruna" type iron deposit, is characterized by its low sulfide content and the presence of magnetite, fluorapatite, and actinolite. This deposit includes a variety of ore types, ranging from massive high-grade iron ore to smaller vein and veinlet ores, that collectively contain hundreds of millions of tons of iron.

Iron ores rich in phosphorus are commonly referred to as Kiruna ore (Solomon R, 2013). The iron oxide-apatite (IOA) deposits of the Kiruna type are vital sources of iron, which is crucial for the production of steel, as well as other elements like rare earth elements (REE), which are necessary for new technologies. Magnetite is the most common iron oxide mineral in Kiruna-type iron ore deposits, but hematite can also be present. These minerals are typically intergrown with other gangue minerals in the ore, making it challenging to separate them during beneficiation. For example, silicate minerals present in such iron ore deposits can impact the processing of the ore, as they may require different beneficiation techniques to effectively remove them from the iron oxide minerals. Apatite is another common mineral present in the deposits of such iron ore. It is a calcium phosphate mineral that can contain significant amounts of phosphorus, and makes the processing of magmatic iron ore challenging, as it can form brittle iron phosphides, which decrease the toughness of the iron and increase its susceptibility to cracking (Lund, 2009).

Physical beneficiation techniques, such as magnetic separation and flotation, are implemented to eliminate apatite and increase the concentration of iron ore. Although gravity separation can be effective in separating dense iron oxide minerals from lighter silicate minerals, it may not be sufficient to separate iron oxide minerals such as magnetite from apatite. Chemical separation techniques may also be utilized to eliminate impurities, such as phosphorous, from the iron ore (Pereira & Papini, 2015).

The Bikilal magnetite-ilmenite deposits within the Western Wollega region have been observed to exhibit characteristics consistent with the Kiruna-type magnetite-ilmenite-apatite end member. These similarities have led to the classification of the Bikilal iron ore deposit as being of the Kiruna type (Solomon R, 2013). This literature review aims to examine the potential of employing magnetic separation techniques to enhance the iron content and recovery of the Bikilal iron ore deposits.

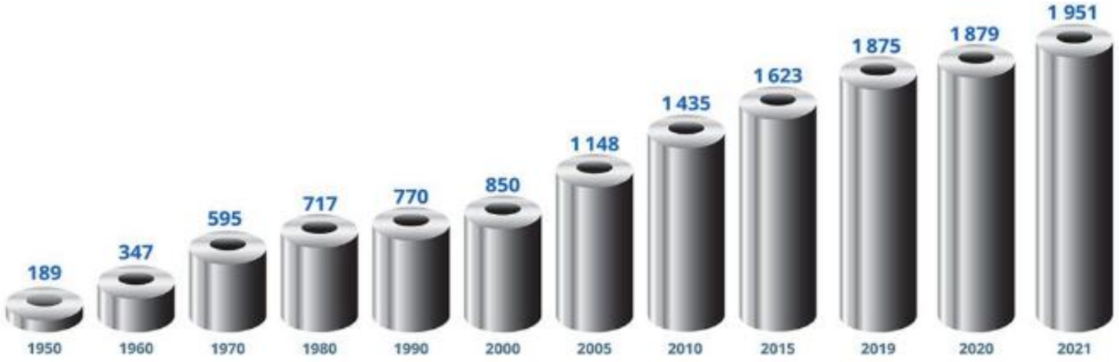

Figure 2.1.Consumption pattern of world crude steel production from 1951 to 2021

Source:(*2022 World Steel in Figures*, World Steel Association)

2.2. MINERALOGY OF IRON BEARING MINERALS

Iron ores are mineral deposits that contain metallic iron and are extracted through economically viable means. Magnetite and hematite are the primary iron oxides used in iron making, with magnetite having a higher content than hematite, making it more highly sought after. Economic magnetite deposits are primarily found in layered igneous rocks, heavy mineral sedimentary deposits, and Early Proterozoic (2.5 to1.6 billion years ago) marine precipitates. In order for a deposit to be considered economically recoverable, it must contain a minimum of 25% iron. This table also lists some important iron ore minerals (refer to Table 2.1).

Table 2.1. List of important iron bearing minerals (Charles Amkiya, 2014)

Mineral	Chemical composition	Theoretical Iron content %	Specific gravity	Mohs hardness
Hematite	Fe_2O_3	70	5.1	5-6
Magnetite	Fe_3O_4	72.4	5.2	5.5-6
Martite	Fe_2O_3	70	5.3	5.5-6.5
Goethite	$FeO(OH)$	62.8	3.3-4.3	5-5.5
Siderite	$FeCO_3$	48.2	4	4

Ore mineralogy related to genesis of Bikilal iron ore deposits as studied by (Solomon R, n.d.) include magnetite, ilmenite, hematite, small amont of sulphides, and apatite. Among these, magnetite and ilmenite are the primary ore minerals. Based on ore microscopic studies, the ore mineral assemblages consist of ilmenite (5-12%), magnetite (20-25%), hematite and small amounts of sulfides in average. In this ore body hematization and martization of both magnetite and ilmenite is very common. The identified gangue minerals within the ore body includes quartz, K-feldspar, Biotite, and chlorite. Minor gangue minerals such as calcite, sphene, rutile and goethite are also present.

2.2.1. Types of iron minerals

Hematite [Fe_2O_3] is an iron oxide mineral with the chemical formula Fe2O3, is widely distributed in various geological settings around the world. It is characterized by its red iron oxide crystals that form in a hexagonal system. The mineral may exhibit varying physical properties, including soft and earthy ocherous, compact, highly porous, granular, or forming dense hard lumps. Fine-grained hematite is typically deep red, bluish red, or brownish red and may have a soft, earthy texture, be compact, or highly porous, among other forms. Crystalline hematite, on the other hand, presents as steel grey with a bright metallic to dull grey luster, and may exhibit a deep bluish to purplish iridescent surface. Coarse-grained hematite, known as specular hematite, may form blocky or platy crystals with a strong micaceous parting, but the cherry red streak is difficult to observe on this variety. Ideally, hematite contains 69.94 percent iron and 30.06 percent oxygen. However, the specific gravity and hardness of the mineral vary, with a range of 4.9 to 5.3 and 5.5 to 6.5, respectively, for hard ore. A variety of hematite, known as maghemite, is found in many orebodies in small quantities and has magnetic properties similar to those of magnetite (07252017105140Monograph on Iron Ore_2, 1957; CharlesAmikiya, 2014).

Martite[Fe_2O_3] is a commonly utilized term to describe particles with a hematite composition, but which exhibit characteristics attributed to its pre-oxidation magnetite parent particle. These particles typically present as iron black with a sub-metallic luster ranging from red to brownish red. Martite may occur in large, powdery masses and, in some instances, may undergo metamorphism to micaceous hematite, although micaceous hematite is not necessarily derived from martite powder. Its occurrence is frequent in strongly oxidized zones overlying magnetite deposits. The chemical composition of Martite[Fe2O3] is identical to that of hematite, having the formula Fe2O3 (07252017105140Monograph on Iron Ore_2, 1957).

Magnetite [Fe_3O_4] is a black magnetic oxide of iron that crystallizes in the isometric system and has a hardness of 5.5 to 6.5. It is the most common species in the magnetite series of spinel mineral group and is the second most important iron-bearing mineral of economic importance. It has a specific gravity 5.17 and magnetic attract ability of 40.18 compared to 100 for pure iron. It occurs as fine- or coarse-grained masses or in octahedral or less commonly dodecahedral crystals. It occurs as veins and stringers in igneous rocks and a lens in crystalline schists. Large deposits are the results of magmatic segregation, and its low-grade deposits occur as disseminations in metamorphic and igneous rocks. It also occurs as a replacement product in sedimentary or metamorphic rocks. It is found as placer deposit as “black sand’ in beach deposits and as banded layers in metamorphic and igneous rocks (07252017105140Monograph on Iron Ore_2, 1957; CharlesAmikiya, 2014).

Goethite [FeO(OH)], limonite [FeO(OH)*nH$_2$O] minerals are hydrated oxides of iron, formed by weathering and hydration. They can be brown to ocherous yellow, black or dark brown to reddish brown, and are often called "brown iron ores". Their specific gravity varies from 3.3 to 4.3 and their hardness is 5.5. They may contain 10 to 14.5 percent combined water and are converted into hematite or magnetite on calcination. When silica is reached out, iron content improves by 10 to 15 percent. These minerals form flakes and needles generally of small dimensions occurring as intergrowths with the original constituents (07252017105140Monograph on Iron Ore_2, 1957)

Siderite [FeCO$_3$], commonly known as spathic ore is an iron carbonate with color ranges from ash gray to brown, with yellow and red stains resulting from oxidation and hydration. Its specific gravity is 3.8 and hardness varies from 3.5 to 4. It crystallizes under rhombohedral division of the hexagonal system. It occurs as sedimentary or replacement deposit (07252017105140Monograph on Iron Ore_2, 1957)

Pyrite [FeS$_2$] is an iron sulfide with a golden yellow color and has a metallic luster. It crystallizes in the cubic system. Its specific gravity is 5.1 and hardness varies from 6 to 6.5. After the sulfur has been removed by calcination, it may be used as iron ore. However, it is not much favored as an iron at present (07252017105140Monograph on Iron Ore_2, 1957).

2.3. BENEFICIATION METHODS FOR IRON ORE

Table 2.2 displays the conventional methods for the beneficiation of iron ores, which include washing and wet scrubbing, gravity concentration (HMS, Spiral, Tables, Multi-gravity separator, Jigs, Cyclone), Magnetic concentrator (Low intensity separator, medium intensity separator, high intensity separator), and Froth flotation. Jigs are utilized for iron ore in the size range of 30mm to 0.5mm and have the capability to treat both coarse and fine feed. Both spirals and tables have a broad range of applications in the treatment of iron ores using gravity and can be employed in almost all circuits of roughing, cleaning, and scavenging, but they are typically implemented at a much smaller scale than magnetic separation. The utilization of flotation process possesses a notable selectivity and is generally employed for handling particle size feed finer than 65 mesh. However, it is often associated with elevated operating costs when compared to magnetic separation (Iron Ore and Its Beneficiation Potential, not dated; Xiong et al., 2015).

Magnetic separation is a critical step in iron ore beneficiation, owing to its exceptional efficiency, high capacity, and low operational costs compared to other methods, such as gravity and flotation. Contemporary magnetic separators are equipped to handle up to 500 metric tons of ore per hour with minimal power and water consumption (Filippov et al., 2014; Xiong et al., 2015). Therefore, it should always be prioritized in iron ore beneficiation flowsheets.

Table 2.2. Common unit operation for beneficiation of iron ore (Iron ore and its Beneficiation potential, n.d; Kumar Panda, n.d.)

Types of process	**Uses for**
Washing and scrubbing	lumpy iron ore
1.Gravity concentration	Heavy and valuable iron ore, based on Sp. Gravity
Heavy media separation	-50+3mm (about 0.12 in) particle size
Spiral	1mm (about 0.04 in) to 3mm
Tables	cleaning and scavenging of -1+0.03mm particles

Multi-gravity separator	ultra-fine particles
Cyclone	both classification and dewatering.
2.Magnetic concentrator	magnetic iron ore, based on magnetic susceptibility
Low-intensity separator	1000 to 2000 gauss
Medium intensity separator	2000 to 7000 gauss
High-intensity separator	7000 to 20000 gauss
Magnetization roasting followed by magnetic separation.	low-grade oxidized iron ore
3. Flotation	finer than 65 mesh

2.3.1. Magnetic separation

Magnetic separation is a technique that employs the distinct magnetic properties of minerals to separate them within a non-uniform magnetic field. This approach is commonly applied to process iron ore and other metallic minerals that are magnetic in nature. The technique is classified as either weak magnetic separation or strong magnetic separation based on the strength of the magnetic field.

It is noted that weak magnetic separation, exhibiting low intensity, is predominantly employed in the processing of strong magnetic minerals, including magnetite (Xiong et al., 2015). Conversely, high-intensity and high-gradient magnetic separation is mainly used for weak magnetic minerals like hematite. A simple magnetic separation circuit is depicted in Figure 2 (Battle et al., 2014). A slurry is passed through a magnetized drum, causing the magnetic material to adhere and be carried to the discharge end. Non-magnetic mineral particles are not affected by the magnetic force and continue to flow as the magnetic products are released. To enhance the separation of paramagnetic particles from gangue, a second pass through a more potent magnetized drum may be applied. To enhance the separation of paramagnetic particles from gangue, a second pass through a more potent magnetized drum may be applied.

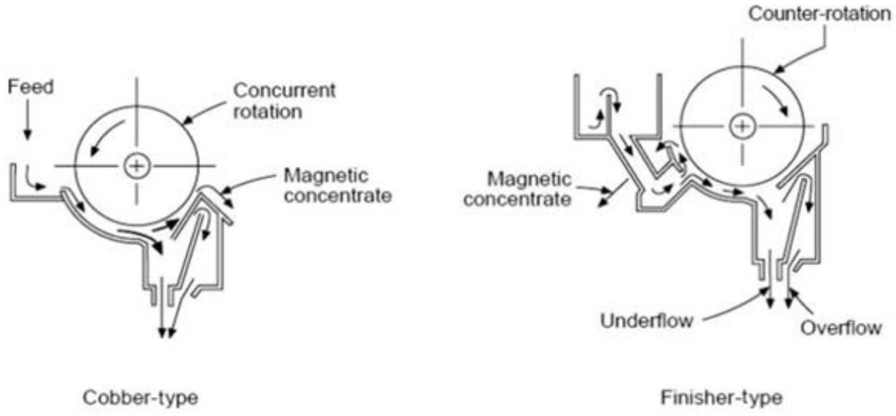

Figure 2.2. Schematic of magnetic separator

2.3.1.1. Principle of magnetic separation

Magnetic Separation is a procedure that utilizes a magnetic separator to isolate mineral particles. When a slurry containing mineral particles is introduced into the magnetic separator, the particles that are susceptible to magnetic forces are subjected to a magnetic field strength (fm) which exceeds the combined influence of gravity, inertia, hydrodynamic resistance, surface forces, and inter-particle forces. This phenomenon is illustrated in Fig 2.3 (Svoboda & Fujita, 2003).

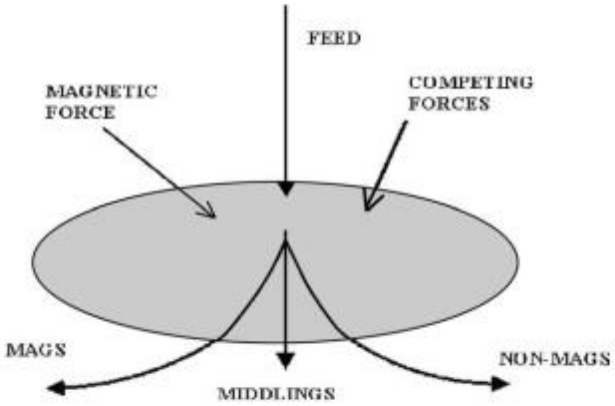

Figure 2.3. Schematic diagram of the process of magnetic separation

The magnetic field required for magnetic separation can be generated either by a permanent magnet or by energizing a coil (Svoboda & Fujita, 2003; Xiong et al., 2015). While the utilization of permanent magnets has long been established in magnetic separators, the demand for this methodology has noticeably escalated in recent years due to the availability of cost-effective ferrite magnets featuring high energy product and coercive force. Moreover, the development of powerful rare-earth permanent magnets has led to the creation of a new generation of permanent magnet-based roll magnetic separators. It is worth noting that a peak magnetic field of 1.9 T, with a very high gradient, can be achieved on the surface of such rolls (Svoboda & Fujita, 2003).

The magnetic force exerted upon a particle is directly proportional to its mass (Kg), as well as the magnetic susceptibility of the particle (m3/Kg), and the intensity (A/m) and gradient (A/m2) of the magnetic field. Magnetic separation involves adjusting the magnetic field intensity or gradient, as the mass and magnetic susceptibility of the particle remain constant. It is crucial to establish a magnetic field of high intensity and gradient to enhance iron recovery from hematite and goethite minerals (Xiong et al., 2015).

2.3.1.2. Magnetic susceptibilities of minerals in iron ore

Magnetic susceptibility is a property of materials that is commonly referred to as their response to an external magnetic field. This property can be precisely determined by comparing the increase in weight of a material exposed to a magnetic field with that of a standard mineral for which the magnetic susceptibility has already been established. Table 2.3 presents some examples of magnetic susceptibility values for iron ore-related minerals.

Table 2.3. Magnetic susceptibility of some iron ore-related minerals (Xiong et al, 2015)

Mineral	Magnetic susceptibility ((10-6m^3/kg	Molecule
Magnetite	625-1156	Fe_3O_4
Martite	602-13.5	Fe_2O_3
Hematite	0.6-2.16	Fe_2O_3
Specularite	3.7	Fe_2O_3
Limonite	0.31-1.0	$2Fe_2O_3.3\text{-}4H_2O$
Siderite	0.7-1.5	$FeCO_3$
Ilmenite	0.34-5	$FeTiO_3$
Quartz	0.0025-0.126	SiO_2
Feldspar	0.063	$KAlSiO_8$, $NaAlSi_3O_8$
Calcite	0.0038	$CaCO_3$
Spodumene	0.82	$LiAl(Si_2O_6)$
Chlorite	0.38-1.13	$(Mg,Fe)_5Al\ (AlSi_3O_{10})\ (OH)_8$
Garnet	0.79-2	$Mg_3Al_2\ (SO4)_3$

Biotite	0.5-6.5	K (Mg,Fe) $_3$ (SiAlO$_{10}$ (OH,Fe) $_2$
Olivine	0.17	(Mg,Fe) SO$_4$
Pyrite	0.34	FeS$_2$
Apatite	0.007-0.142	Ca$_5$ (PO$_4$)$_3$F

2.3.1.2.1 Iron ore minerals

Iron ores are typically categorized into two principal groups based on their magnetic properties, namely strongly magnetic iron ores, which include magnetite (72.4% Fe), and weakly magnetic iron ores, which encompass martite (70.0% Fe), hematite (70.0% Fe), specularite (70.0% Fe), limonite (57.14–59.89% Fe), and siderite (48.2% Fe). Magnetite is ideally suited for magnetic separation due to its high magnetic susceptibility, but the recovery of oxidized iron ores, such as specularite, hematite, and martite, using magnetic separators is much more challenging. Among these oxidized iron ores, specularite is the most responsive to magnetic fields and can be upgraded using magnetic separation, making it easier to recover compared to martite and hematite. Conversely, limonite is less responsive to magnetic fields and difficult to recover using magnetic separation. Additionally, siderite contains only 48.2% Fe, making it impossible to achieve a high iron grade for siderite concentrates (Xiong et al., 2015).

2.3.1.2.2 Gangue minerals in iron ores.

Iron ore is composed of a diverse array of minerals, including white minerals (quartz, calcite, and feldspar gangue), possess a magnetic susceptibility near zero and can be easily separated from the ore through magnetic separation. However, dark minerals (spodumene, garnet, biotite) which have a magnetic susceptibility similar to that of oxidized iron ores, pose a challenge in separating them from oxidized iron ores via magnetic separation. Moreover, pyrite and apatite, which are weakly magnetic and contain deleterious elements Sulfur (S) and Phosphorus (P), are deleterious minerals commonly found in iron ore. Although magnetic separation can partially remove these minerals from oxidized iron ores (Xiong et al., 2015), their presence can impact the quality of the final product.

2.3.2. Magnetic Methods for Beneficiation of Iron ores.

Magnetic separation is a process that utilizes high-intensity magnetic fields to differentiate between iron ore particles and non-magnetic mineral particles. The effectiveness of this process is determined by the relative strength of the magnetic field and is classified as either wet or dry, depending on the type of ore being processed. The choice of separator is influenced by several factors, including the particle size distribution, the distribution of magnetic properties among the particles, and the required processing capacity. Wet High-Intensity Magnetic Separation (WHIMS) is often used for treating fine, weakly magnetic iron minerals, while Wet Low-Intensity Magnetic Separation (WLIMS) is favored for recovering iron-containing strongly magnetic minerals. (Siame et al., n.d; Svoboda & Fujita., 2003; Filippov et al., 2014).

2.3.2.2 Different approaches for treating iron ore.

Sis et al. (2021) conducted an investigation into the efficacy of various technologies for beneficiating iron ore from the Doanşehir region in Malatya. The ore is primarily composed of magnetite, with additional presence of magnesioferrite, ferro-actinolite, and calcite minerals. The study revealed that particle size has a significant impact on concentration, with finer particles producing cleaner concentrates for a specific separation process. Wet magnetic separation was found to yield comparable results to gravimetric methods, with a concentrate containing 65.66% Fe and 0.38% K2O+Na2O, and a recovery of 78.11%. Baawuah et al. (2020) conducted a study on the performance of a pneumatic planar magnetic separator (PMS) for the dry beneficiation of a selected magnetite ore. The results demonstrated that PMS is a viable option and can replace the Davis tube recovery tester (DTR) in arid region operations, improving the magnetite concentrate grade and purity. Dwari et al. (2013) investigated the suitability of a low-grade siliceous iron ore sample for physical beneficiation by magnetic separation. The study found that the sample contained magnetite, hematite, and goethite as major opaque oxide minerals, while quartz and kaolinite were present as gangue minerals. The study also found that it was possible to obtain an overall concentrate with 54% Fe and 32.4% weight recovery by combining size reduction followed by low-intensity magnetic separation (LIMS) and high-intensity magnetic separation (HIMS). Seifelnassr et al. (n.d.) conducted a study to explore the viability of enhancing the recently discovered Sudanese low-grade ore through the implementation of gravity and magnetic separation techniques. The investigation revealed that a two-stage separation process, comprising roughing and cleaning, led to the retrieval of a high-grade concentrate with an iron content of approximately 64% and a recovery rate of 72%. The study concludes that by utilizing a high-intensity magnetic separator, a magnetic concentrate with an iron content of 64.2% and 0.24% BaO can be obtained from a feed containing 44% iron and 20% BaO, at a feed size fraction of 0.106 + 0.074 mm.

CHAPTER THREE: EXPERIMENTAL WORKS

The experimental work for this research project was conducted according to the Figure 3.1, which shows the main activities performed, starting from the sample preparation to the evaluation of the final magnetic product concentration.

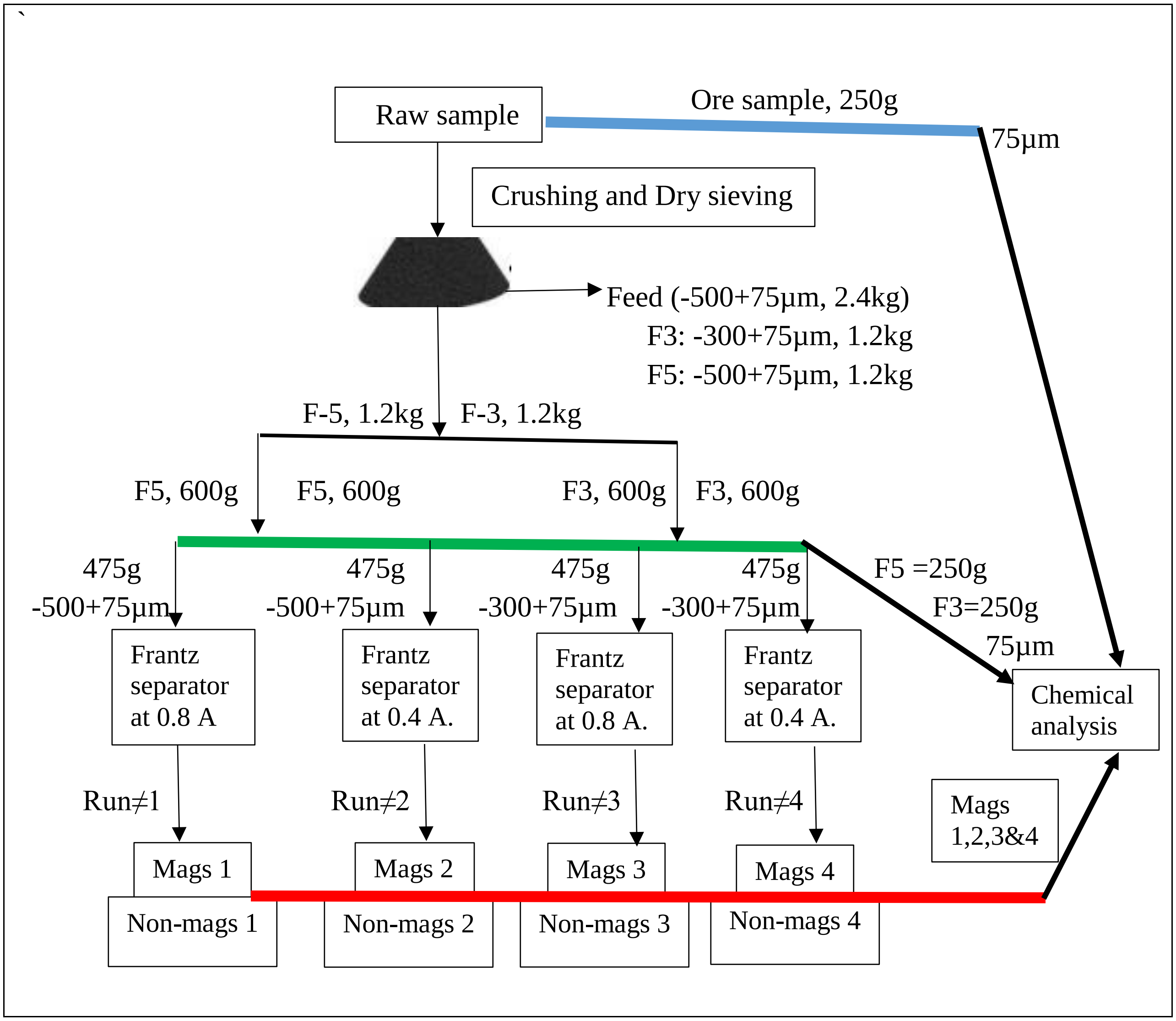

Figure 3.1.Simplified flow sheet of experimental studies

3.1. MATERIALS AND EQUIPMENT

The main material used in the experiment was Bikilal iron ore sample, which was obtained from Central Laboratory of Geological Survey Institute (GSI) of Ethiopia.

- For sample preparation, a jaw crusher was used to crush the ore into smaller pieces. Then, attrition mill was used to further crush the ore into desired sizes. Finally, a sieve shaker with standard aperture size was used to separate the powder into two desired size fractions.

- To recover the strongly magnetic materials before separation, a one held magnet was applied to the ore powder. This magnet had a magnetic field strength of 0.15 T.

- For magnetic separation, a laboratory scale Frantz Magnetic Separator was used. This separator had a magnetic field that could be varied from 0 to 2A. The separator was supplied by Frantz Low Field Control Model LFC-2, which controlled the current and voltage of the electromagnet.

- To measure and analyze the iron grade and recovery of the separated fractions, a digital balance and a complete silicate analysis with an atomic absorption spectroscopy were used. The digital balance had an accuracy of 0.01 g. The atomic absorption spectroscopy had a detection limit of 0.01 ppm for iron oxide mineral.

- To design the experiment, record the data and analyze the results, a computer with Design Expert v13.0.5.0 software was used. This was a software for statistical analysis and data visualization.

3.2. PROCEDURE

3.2.1. Sample Preparation

The ore sample and feed preparation phase were undertaken to offer representative samples for chemical analysis and beneficiation. Feed preparation for beneficiation study can involve steps such as crushing and sizing to reduce the size of the ore particles and classify particles of different sizes to obtain a representative feed fraction for the experiment. The Bikilal iron ore sample was obtained from the Central Geological Laboratory of the Geological Survey Institute of Ethiopia. The sample was taken from different borehole log that describe the depth of the deposit to ensure the representation of the orebody. The acquired sample was then being crushed with a laboratory jaw crusher and classified with a standard laboratory sieve shaker to achieve a particle size between 500 and 75 µm.

Figure 3.2. The process of Crushing Bikilal iron ore sample at the AAiT laboratory

Afterward, the sample was sieved and weighted to obtain representative samples for chemical analysis and beneficiation study: -500 + 75 µm and -300 + 75 µm using ASTM standard aperture sizes of 500µm, 300µm, and 75µm. This process was carried out at the Addis Ababa Technology Institute Laboratory. The prepared fractions were divided into 475g each and placed in plastic bags. Each sample was labeled with its size fraction and were taken to laboratory.

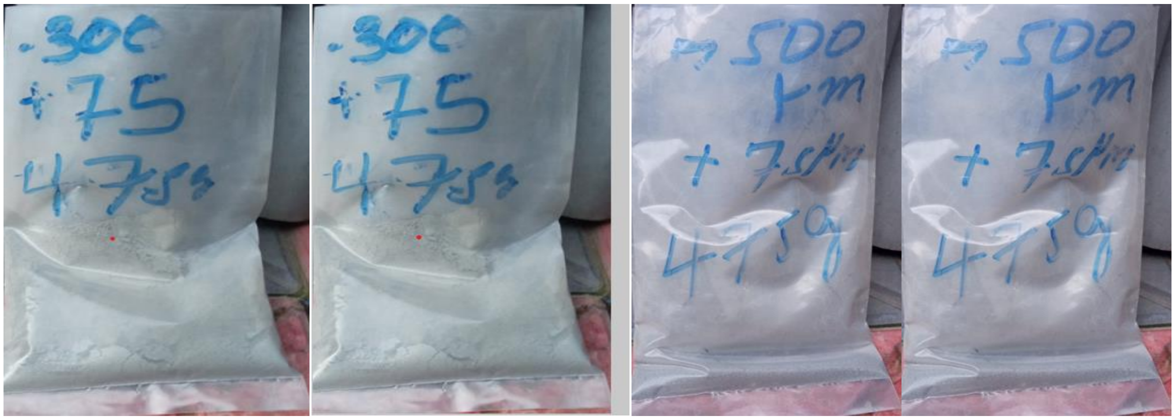

Figure 3.3. Prepared raw sample for beneficiation study

Figure 3.4. ASTM standard sieve shaker at AAiT laboratory

3.2.2. Frantz Magnetic separation test work.

The prepared samples from the sample preparation phase were taken to the Central Geological Laboratory, where they were separated from one another. Prior to magnetic separation, a one hand held magnet was utilized at the laboratory to separately recover and concentrate the strongly magnetic materials from each prepared fraction. This step was necessary to prevent clogging of the separator and ensure optimal performance. The beneficiation of prepared Bikilal iron sample was then conducted using a laboratory scale Frantz magnetic separator at the laboratory. The separator was set at different magnetic field intensities by adjusting the electric current that flows through the electromagnet. The current was set to the desired level and pulsed between selected high: 0.4 A and low: 0.8 A values at selected frequencies. The prepared fractions were then subjected to the separator at this adjusted current to produce the magnetic and non-magnetic products. The magnetic and non-magnetic particles was collected in a separate container based on their magnetic susceptibility.

Figure 3.5. Adjustment made for current during separation process

3.2.3. Evaluation of separation process

To evaluate the performance and efficiency of the Frantz laboratory magnetic separation process, chemical analysis of the ore sample, feed and the magnetic concentrate products generated from the test work was performed using an AAS. It was used to determine the grade that can be used to reflect the quality of iron particles (%Fe_2O_3) present in the sample, feed and concentrate products by performing a complete silicate analysis method at the Geological Laboratory. For this purpose, seven samples were pulverized to 200 mesh (75µm): one for the obtained samples; two samples for the prepared feed size fraction and another for the four magnetic products produced after the Frantz laboratory magnetic separation process. Pulverization ensured uniform particle size distribution and increased the surface area for accurate analysis. This pulverization was performed in the Central Geological Laboratory of Ethiopia.

After the pulverization, the samples were carefully transferred to the laboratory technician responsible for the analysis. The pulverized samples were then analyzed using the Atomic Absorption Spectroscopy method shown in Figure 3.6, which allowed for the quantification of specific oxide minerals present in the ore samples and concentrate products.

The AAS technique employed the absorption of light at characteristic wavelengths by the sample, providing information about the chemical composition. Throughout the analysis, strict quality control measures were implemented to ensure the accuracy and reliability of the obtained results. These measures included calibrating the AAS instrument with standard reference materials, performing replicates, and monitoring instrumental parameters to minimize any potential sources of error.

Figure 3.6. AAS calibrated for chemical analysis

The performance of the separation tests was then measured based on the chemical analysis of the test products. To evaluate the performance of the process, iron (Fe) recovery values of each test were calculated based on the weight of the magnetic concentrates and the initial iron content of the feed particle size and test products. The following equation (equation 1) was used for the evaluation of separation test, and the calculation and results are presented in the results and discussion section 4.3.5.

- ✓ $$\text{Fe recovery} = \frac{\text{C.c}}{\text{F.f}} \text{x}100 \qquad \text{equation (1)},$$

Where C is the mass of the concentrate, c is the percentage of valuable mineral in the concentrate and F is mass of the feed fraction, and f is the percentage of the valuable mineral in the feed.

3.3. EXPERIMENTAL DESIGN

The obtained data from the Frantz laboratory magnetic separation process was subjected to statistical analysis using Design Expert v13.0.5 software. This software allows for the identification of trends, correlations, and optimization of process parameters to determine the optimum conditions for maximizing the iron grade and recovery.

An analysis of Variance (ANOVA) was performed on the collected data to determine the significance of two factors and their interactions on the iron grade and recovery. The factors considered in this study were feed size and current each with two levels. The responses of interest were the iron recovery and grade achieved from the magnetic separation process. The analysis aimed to identify the main parameters that significantly influenced the effectiveness of Frantz laboratory separator and to determine the optimal combination of these parameters for achieving the highest iron grade and recovery. The current was chosen as a factor because it determines the strength of attraction between the magnetic particles and the separator. The feed size was chosen as another factor because it affects the liberation and distribution of iron minerals in the ore.

The design of the experiments was done using Design Expert v13.0.5 software, which is a statistical software for design of experiments and optimization. The software was used for determining the number of experimental runs for independent variables and generated a full factorial design matrix with a total of four runs. It facilitated the analysis of the data and provided insights in to the relationship between the factors and responses.

Tabe 3.1. Design summary

File Version	13.0.5.0		
Study Type	Factorial	**Subtype**	Randomized
Design Type	Full Factorial	**Runs**	4.00
Design Model	2FI	**Blocks**	No Blocks
Center points	0.0000	**Build Time (ms)**	57.00

Tabe 3.2. Experimental variables and the actual values of the research variables

Factor	**Name**	**Units**	**Type**	**Subtype**	**Minimum**	**Maximum**		
A	Feed size	Micron	Categoric	Nominal	-300+75	-500+75	**Levels:**	2.00
B	Current	Ampere	Categoric	Nominal	0.4	0.8	**Levels:**	2.00

3.4. PRECAUTIONS AND SAFETY MEASURES

The following precautions and safety measures were taken during the experimental work:

- ✓ The sample was handled with care to avoid contamination or loss of material.
- ✓ The equipment was checked for proper functioning before each experiment.
- ✓ The current was turned off before changing the feed size fraction or collecting the concentrate.

- ✓ The magnetic separator chute was cleaned after each experiment.
- ✓ The AAS analysis method was performed with accuracy and precision to avoid errors in measuring the iron content.

CHAPTER FOUR: RESULT AND DISCUSSION

The results and discussion section of this research project presents the findings and analysis of the beneficiation test conducted on the Bikilal iron ore sample using a Frantz Laboratory Magnetic Separator. The main objective of this study was to investigate the potential of this iron ore deposit for upgrading by magnetic separation method. The specific objectives were to review previous studies on the mineralogy of the ore, to characterize its chemistry, and to examine the effects of particle size and magnetic field intensity on the separation efficiency.

The results and discussion section are organized as follows:

A. A brief summary of the previous studies on the mineralogy of the Bikilal iron ore deposits is given, highlighting the main mineral phases present in the ore.

B. The chemical composition of the iron ore sample is reported, comparing them with the literature data and explaining their implications for the beneficiation potential of the ore.

C. The beneficiation test parameters are described, the results of the beneficiation test are presented and discussed, showing the mass yield, iron grade, and iron recovery of each magnetic fraction obtained at different particle sizes and magnetic field intensities.

D. By using the statistical analysis of the experimental results, the effects of particle size and magnetic field intensity on the separation efficiency are discussed, analyzing how these factors influence the iron grade and iron recovery of each magnetic fraction.

E. A summary table and a graphical representation of the results are provided for comparison and evaluation. Finally, some recommendations for future studies and applications are given, based on the findings and conclusions of this research project.

4.1.MINERALOGICAL CHARACTERIZATION OF BIKILAL IRON ORE

The mineralogical characterization of the iron ore sample is of utmost importance in the study of low-grade iron ore, as it aids in determining the most suitable method for concentration. Previous studies on the Bikilal iron ore have identified the mineral phases present in the ore sample, providing valuable insights into its mineralogical composition and potential beneficiation strategies. The Geological Survey of Ethiopia has documented the mineralogy of the Bikilal iron ore deposit, indicating that it is a vanadium-bearing titanomagnetite ore.

The dominant minerals identified in the Bikilal iron ore sample are magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$). These minerals are commonly found in Bikilal iron ore deposits and are considered key minerals of interest due to the high iron content of magnetite. The average mineralogic composition, as reported by the Geological Survey of Ethiopia, indicates that the subsurface ore consists of approximately 40% magnetite, 29% ilmenite, 2-2.5% pyrrhotite and pyrite, 0.6% apatite, 1% chalcopyrite and pentlandite, and approximately 30% amphibole, chlorite, pyroxene, olivine, among others. On the surface, ilmenite content averages around 35%.

In addition to magnetite and ilmenite, the Bikilal iron ore may contain gangue minerals such as quartz, K-feldspar, phosphorus, and trace amounts of sulfur. It is essential to further characterize these minerals to assess their influence on the ore's behavior during the beneficiation process.

4.1.1. Magnetite

In this study, magnetite is identified as a primary iron ore mineral of economic interest due to its strong magnetic properties. Its high iron content (72.4 % Fe) makes it a desirable mineral for metal iron production. The presence of magnetite being ferromagnetic in the Bikilal iron ore, therefore, means that magnetic separation can be applied, in principle, to concentrate and upgrade the iron bearing mineral content of the ore. Magnetic separation relies on the strong magnetic susceptibility of magnetite to selectively separate it from other less-magnetic and non-magnetic minerals and impurities present in the ore. By exploiting magnetite's high magnetic properties, it is therefore possible to improve the iron grade and recovery of the low-grade Bikilal iron ore by magnetic separation method.

4.1.2. Ilmenite

Ilmenite is another important mineral present in the Bikilal iron ore. While ilmenite contains lower iron content compared to magnetite, it is a valuable mineral due to its titanium content than its iron content. Ilmenite forms ex-solved crystals within magnetite in the Bikilal iron ore deposit, which can affect the separation process. Understanding the distribution and characteristics of associated ilmenite mineral within the ore is crucial for an evaluation to produce by-product ilmenite mineral opportunities from the low-grade Bikilal iron ore deposits. Additionally, ilmenite's presence may require further considerations during processing due to its impact on the quality and composition of the final iron concentrate.

4.1.3. Implications for the Concentration Process

The presence of magnetite, ilmenite and other deleterious silicate, kaolinite, calcite and magnesite and phosphate minerals in the Bikilal iron ore provides several implications for their beneficiation process:

4.1.3.1. Implication for the Magnetic Separation

The highly strong magnetic property of magnetite enables selection of magnetic separation, allowing for the recovery of magnetic minerals from the ore. By utilizing magnetic separation techniques, it is possible to concentrate the magnetite-rich fraction and upgrade the iron grade.

4.1.3.2. Implication for the process optimization

The presence of ilmenite as ex-solved crystals within magnetite in the Bikilal iron ore deposit necessitates careful process optimization. The liberation and particle size distribution of ilmenite need to be considered to maximize the recovery and grade of both iron and titanium minerals. Adjustments in the magnetic separation parameters and understanding the behavior of the magnetite-ilmenite association can help improve the efficiency of the beneficiation process.

4.1.3.3. Gangue mineral characterization

The presence of gangue minerals such as quartz, K-feldspar, phosphorus, and trace amounts of sulfur also affects the beneficiation process of the Bikilal iron ore. These minerals may introduce challenges during processing, including increased energy requirements, or undesirable effects on the quality of the final iron concentrate. Proper characterization and understanding of their behavior can guide the development of suitable processing techniques to minimize their impact.

In summary, the dissemination of iron values of Bikilal iron ore (magnetite) in particles of different magnetic susceptibilities such as quartz added advantage to operator's magnetic separation choice over other beneficiation technique commonly used to treat iron ores. This difference possibly offers opportunities for effective magnetic separation in concentration of Bikilal iron ore.

4.2. CHEMICAL CHARACTERIZATION OF THE ORE

The second objective of this study was to analyze the chemical composition of the obtained ore samples and specific feed size fractions for beneficiation study, and to evaluate the quality and potential of the ore. The complete silicate analysis of the ore samples and specific feed fractions was carried out using the Atomic Absorption Spectroscopy method at the Central Geological Laboratory of Geological Survey Institute of Ethiopia (GSI). Due to limitations such as insecurity in the area and restricted access, representative samples from the potential area of the Bikilal iron ore deposits could not be collected. As a result, the Core samples were provided by Core archives of GSI. It should be noted that the acquired samples were not fresh and small in size, which may not fully represent the entire deposits composition.

Table 4.1 presents the size wise complete silicate analysis of Bikilal iron ore sample used in this project work. The table shows the major and minor oxides of the constituent minerals with the iron oxide (Fe_2O_3) content varies from 19.00 to 19.80 % among the fractions and samples. It is clear that the value of iron content observed in both size fraction and sample is low-grade in terms of iron ore mineral content, in the range of 19.50% Fe_2O_3, and contains a significant concentration of material deleterious to iron ore products such as silica, alumina, calcium oxide, magnesium oxide, sodium oxide, phosphorus pentoxide, and titanium dioxide, in the range of 46 % SiO_2, 13.96 % Al_2O_3, 8.5 % CaO, 5.5 % MgO, 3% Na_2O, 1.5 % P_2O_5, 1.2 % TiO_2 respectively. The rest of undesired constituent is negligible, ranging from 0 to 1% each.

Table 4.1. Complete silicate analytical results of Bikilal iron ore and head feed fractions

`	**Grade, wt%**								
Size fraction, μm	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	Na_2O	P_2O_5	TiO_2	LOI
DA-12	19.00	46.16	9.96	8.06	9.06	3.72	1.30	1.28	1.06
F3: -300 +75	19.80	45.80	15.88	8.56	4.38	2.14	1.60	1.17	1.05
F5: -500+75	19.50	45.98	16.04	9.34	3.14	2.52	1.55	1.24	0.89

As demonstrated in the table, the Bikilal iron ore sample is primarily composed of iron oxide, with silica, alumina, and magnesia being the predominant gangue minerals. The high concentration of these gangue minerals in the chemical composition of the Bikilal iron ore presents several challenges in the downstream processing of the ore, including:

- The presence of high silica content (46% SiO_2), reduces the iron grade and increases the slag formation during production of pig iron in the blast furnace.
- The presence of high alumina content 13.96 % Al_2O_3, affects the viscosity and fluidity of the slag and increases the refractory wear.
- The presence of high phosphorus content 1.5 % P_2O_5, lowers the quality and strength of the iron and steel products.

- The presence of high titanium content 1.2 % TiO_2, forms complex oxides that are difficult to reduce and separate.

In general, the results of the the complete silicate analysis of the Bikilal iron ore sample the Bikilal iron ore sample used in this project indicate that the ore cannot be utilized directly in a blast furnace or other iron-making processes due to its low iron content. Consequently, several stages of physical beneficiation processes are required to improve the iron grade of the ore.

The results of the analysis were compared with typical values of iron ore deposits in Ethiopia, which have an average iron content ranging from 20% to 40% with some deposits reaching up to 60% (GSI). The iron content of the Bikilal iron ore sample is lower than the average, indicating that it requires more beneficiation to increase the iron grade of the ore. However, the phosphorus and titanium contents of the Bikilal iron ore are lower than some other deposits, which are considered deleterious elements in iron ore processing. Therefore, the Bikilal iron ore is classified as a low-grade iron ore that requires beneficiation for its further utilization in metallurgical applications.

4.3. BENEFICIATION TECHNIQUE

The beneficiation technique used in this study was laboratory scale magnetic separation, which is a physical process that use electro-magnet to separate minerals according to their magnetic properties. The magnetic properties of minerals depend on their magnetic susceptibility, which is influenced by a number of variables. The size of the ore particles and the strength of the magnetic field play a vital role among them. The purpose of magnetic separation is to improve the iron grade of the Bikilal iron ore by removing the non-magnetic gangue minerals from the magnetic iron-bearing minerals.

4.3.1. Equipment Descriptions

The equipment used for magnetic separation was a Frantz laboratory magnetic separator model LFC-2, which is a device that allows precise control of the magnetic field intensity and direction. The device consists of four main components: an electromagnet, a feed hopper, a splitter, and a collection bin. The electromagnet produces a horizontal magnetic field that can be adjusted by changing the current from 0 to 2 amperes. The feed hopper receives the ore fractions and feeds them to the splitter, which splits them into two streams: one that is attracted by the magnetic field and collected in the magnetic bin, and another that is unaffected by the field and collected in the non-magnetic bin.

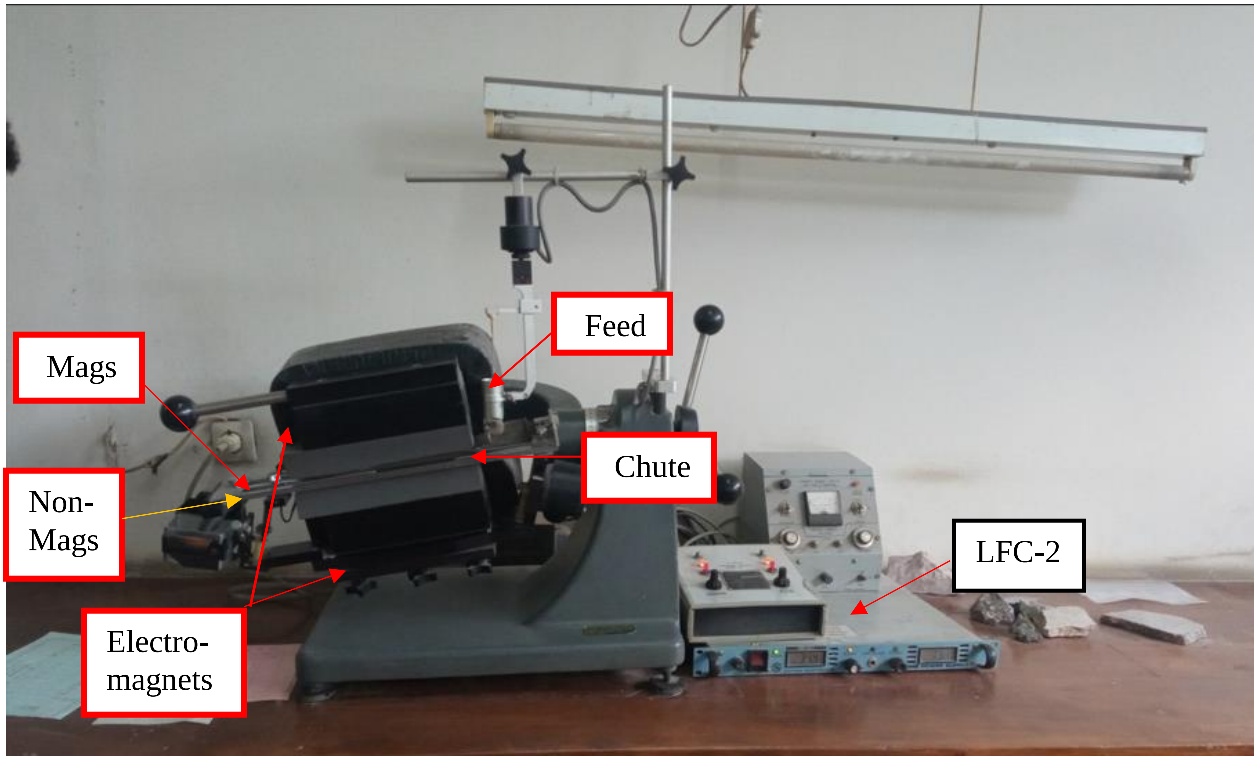

Figure 4. 1. Frantz laboratory magnetic separator used in the present investigation

4.3.2. Evaluation of Separation tests

During the magnetic separation process, there are parameters that can prevent effective concentration of valuable minerals such as feed characteristics including feed particle size, and process parameters such as magnetic force exerted on a mineral particle. Therefore, a total of four experiments were conducted, to evaluate the combined effects of these process parameters on the performance and efficiency of Frantz Laboratory Magnetic Separator. The grade and recovery are the most used performance evaluation parameters in beneficiation processes (separation efficiency). The results of the magnetic separation process with Frantz laboratory magnetic separator are presented and discussed in this section. The results are organized according to the following categories:

4.3.2.1. Feed size fractions

The raw feed fraction is one of the critical parameter that can affect the separation efficiency of the magnetic separation methods. The optimal size range for separating valuable magnetic iron minerals from non-magnetic gangue minerals is -500 + 75 µm. Based on this Criterion and previous study that used both gravity and low intensity magnetic separation for concentrating Bikilal iron ore, two feed size fraction were selected for this study: -300 + 75 µm and -500 + 75 µm. These fractions were also chosen to avoid overgrinding and loss of valuable materials, as well as to investigate the effect of particle size on the magnetic susceptibility of the minerals present in the ore samples.

4.3.2.2. Current settings

The current that passes through an electromagnetic coil generates a magnetic field that can capture magnetic mineral of interest. The current setting is another critical parameter that affect the separation efficiency of electromagnetic separation methods. The previous mineralogical study of the Bikilal iron ore sample revealed the presence of ferro-magnetic minerals (magnetite), paramagnetic minerals (ilmenite and small amount of hematite), and diamagnetic minerals (quartz, feldspar, kaolinite, calcite and magnesite). These minerals have different magnetic susceptibilities and respond differently to the applied magnetic field. Therefore, two current settings were selected for this study: 0.4 A and 0.8 A.

These settings were also considered the range of current (0 to 2A) that can be applied by the Frantz laboratory magnetic separator and the expected effect of current used to generate the magnetic field intensity that can be applied to achieve magnetization of the magnetic particles present in the ore samples such as magnetite, and reverse the direction of current to achieve demagnetization of those highly magnetized magnetite particles for efficient separation.

4.3.2.3. Characterization and Analysis of Magnetic Product (Mags)

The magnetic product (Mags) are the streams that were deflected by the magnetic field and collected in the magnetic bin during the Frantz magnetic separation process. Four magnetic concentrates were obtained from the two feed fractions (F-3 and F-5) at two different current settings (0.4A and 0.8A). These magnetic product (mags) were labeled as C-5-8, C-5-4, C-3-8 and C-3-4, respectively. The mags where then pulverized and analyzed for their chemical composition focusing on the iron oxide and silicon dioxide contents. The mass recovery and grade of each magnetic product are shown in Table 4.2.

Table 4.2. Results of Frantz Magnetic separation test

Sample	Mass recovery, wt %	Grade, wt.%	
		Fe_2O_3	SiO_2
C-5-8 mags	65.2	25.02	33.64
C-5-4 mags	64	20.84	41.62
C-3-8 mags	57.2	31.18	28.94
C-3-4 mags	55.8	26.64	37.3

The results indicate that the Frantz laboratory magnetic separation process was effective in enriching the iron content of the samples, as the Fe_2O_3 grade increased by 11.38 wt.% in the mags compared to the feed sample (Table 4.1). The SiO_2 content, which represents the main gangue mineral (quartz), decreased by more than 26 wt.% in the mags, indicating a good separation of iron minerals from non-magnetic impurities.

The results also reveal that the mass recovery and grade of the magnetic products were influenced by the feed particle size and the current setting of the Frantz laboratory magnetic separator. The mass recovery was higher for the coarser feed size (F-5) than the finer size (F-3), especially at higher current (0.8A). This implies that the coarser particles had higher magnetic susceptibility and were more easily attracted by the magnetic field. However, the grade was higher for the finer feed size, suggesting that the finer particles had more liberated iron minerals and less non-magnetic gangue minerals.

The SiO_2 content also varied with the feed particle size and the current setting, showing an inverse relationship with the Fe_2O_3 content. The SiO_2 content was lower for the finer feed size and higher for higher current, indicating that these factors affected the degree of separation of quartz from iron minerals.

In summary, the Frantz laboratory magnetic separation process was successful in producing a rougher concentrate of iron minerals from the Bikilal iron ore sample, with satisfactory mass recovery and grade values. The process parameters, such as feed particle size and current setting, had significant effects on the separation efficiency and should be optimized for further cleaning and scavenging stage.

4.3.2.4. Determination of Iron grade and recovery

Iron grade and recovery are two key indicators that reflect the quality and quantity of the products produced after certain separation process in mineral processing applications. Therefore, the grade and recovery obtained from Frantz separation test were measured and recorded. The evaluation of these parameters provides important insights in to the performance of the Frantz laboratory scale magnetic separation process in upgrading the iron values of the Bikilal iron ore. The iron grade is the percentage of valuable iron minerals (%Fe_2O_3) in the ore samples or fractions. It indicates the quality and concentration of iron in the sample fractions and magnetic products produced through the separation process. The iron recovery is the percentage of iron oxide (%Fe_2O_3) in weight that was recovered in the magnetic concentrates from the ore samples. It indicates the efficiency and performance of the beneficiation process in separating the iron bearing minerals from the ore samples.

4.3.3. Data analysis and interpretations

The data and results obtained from each combination of tests are shown in tables and figures, with appropriate labels or captions. They are also analyzed and interpreted using line plots and tables. Figure 4.1 and 4.2 shows the relationship between feed size, current, iron grade, and iron recovery for each experiment. Table 4.3 presents the results of iron grade and iron recovery for each experiment, indicating the percentage of the Fe_2O_3 in the magnetic concentrates. The recovery parameters were calculated based on the equation (1) above as follows:

- For experiment 1 using feed size fraction: -500 + 75 µm and 0.8 A.

$$Fe\ recovery\ (\%) = \frac{C5-8x\ c5-8}{F5x\ f5}x100$$

$$= \frac{310gm\ x\ 25.02}{475\ gmx\ 19.5}x100$$

= **83.73%**

- For experiment 2 using feed size fraction: -500 + 75 µm and 0.4A.

$$Fe\ recovery\ (\%) = \frac{C5-4x\ c5-4}{F5x\ f5}x100$$

$$= \frac{304gm\ x\ 20.84}{475\ gmx\ 19.5}x100$$

= **68.63%**

- For experiment 3 using feed size fraction: -300 + 75 µm and 0.8A.

$$Fe\ recovery\ (\%) = \frac{C3-8\ x\ c3-8}{F3x\ f3}x100$$

$$= \frac{272gm\ x\ 31.18}{475\ gmx\ 19.8}x100$$

= **90.17%**

- For experiment 4 using feed size fraction: -300 + 75 µm and 0.4A.

$$Fe\ recovery\ (\%) = \frac{C3{-}4x\ c3{-}4}{F3x\ f3} x100$$

$$= \frac{265gm\ x\ 26.64}{475gm\ x\ 19.8} x100$$

= **<u>75.63%</u>**

Table 4.3. Summary of the Fe Recovery calculations for the Mags

	Factors		**Response**	
Run	A: Feed size (µm)	B: Current (A)	R1: Fe grade (%)	R2: Fe recovery (%)
1	-500+75	0.8	25.02	83.73
2	-500+75	0.4	20.84	68.63
3	-300+75	0.8	31.18	90.17
4	-300+75	0.4	26.64	75.63

4.3.3.1. Experiment 1

As shown from Table 4.3. and Figure (4.2 and 4.3), the observed value for Fe grade and recovery that received larger particle feed size (-500 + 75 µm) and higher intensity (0.8 A) was about 25.02% and 83.73% respectively. The data and results of this experiment show that the magnetic product weight was 310 g, which is 65.3% of the head feed size fraction weight (475 g). The non-magnetic fraction weight was 165 g, which is 34.7% of the feed size fraction weight. The iron grade in the magnetic product was 25.02%, which is higher than the iron grade in the feed size fraction (19.5%). The iron recovery in the magnetic fraction was 83.73%, which is higher than all the experiments, except Experiment 3. This indicates that using a high current (0.8 A) and a coarse feed size fraction (-500 + 75 µm) resulted in a high efficiency but low concentration of iron in the magnetic concentrates. It suggested that using a high current (0.8 A) and a coarse feed size fraction (-500 + 75 µm) can be a good option for maximizing iron recovery, but not iron grade, as it may result in a high quantity but low quality of iron ore concentrates.

4.3.3.2. Experiment 2

As shown from Table 4.3 and Figure (4.2 and 4.3), the observed value for Fe grade and recovery that received larger particle feed size (-500 + 75 µm) and lower intensity (0.4 A) was about 20.84% and 68.63% respectively. The data and results of this experiment show that the magnetic product weight was 304 g, which is 64% of the head feed size fraction weight (475 g). The non-magnetic fraction weight was 171 g, which is 36% of the feed size fraction weight. The iron grade in the magnetic product was 20.84%, which is higher than the iron grade in the feed size fraction (19.5%). The iron recovery in the magnetic fraction was 68.63%, which is lower than all the experiments, except Experiment 4. This indicates that using a low current (0.4 A) and a coarse feed size fraction (-500 + 75 µm) resulted in a low concentration and efficiency of iron in the magnetic concentrates. It suggested that using a low current (0.4 A) and a coarse feed size fraction (-500 + 75 µm) can be a poor option for both iron grade and recovery, as it may result in a low quality and quantity of iron ore concentrates.

4.3.3.3. Experiment 3

As it can be shown from the Table 4.3 above and Figure below, the observed value for Fe grade and recovery that received smaller particle feed size (-300 + 75 µm) and higher intensity (0.8 A) was about 31.18 % and 90.17 % respectively. The data and results of this experiment shows that the magnetic product weight was 272 g, which is 57.2% of the head feed size fraction weight (475 g). The non-magnetic fraction weight was 203 g, which is 42.8% of the feed size fraction weight. The iron grade in the magnetic product was 31.18%, which is higher than the iron grade in the feed size fraction (19.8%). The iron recovery in the magnetic fraction was 90.17%, which is higher than all the experiments, second only to Experiment 1. This indicates that using a high current (0.8 A) and a fine feed size fraction (-300 + 75 µm) resulted in a high concentration and efficiency of iron in the magnetic concentrates. It suggested that using a high current (0.8 A) and a fine feed size fraction (-300 + 75 µm) can be a good option for maximizing both iron grade and recovery, as it may result in a high quality and quantity of iron ore concentrates for the first stage magnetic separation concentrate.

4.3.3.4. Experiment 4

As shown from Table 4.3 and Figure (4.2 and 4.3), the observed value for Fe grade and recovery that received smaller particle feed size (-300 + 75 µm) and lower intensity (0.4 A) was about 26.64% and 75.63% respectively. The data and results of this experiment show that the magnetic product weight was 265 g, which is 55.8% of the head feed size fraction weight (475 g). The non-magnetic fraction weight was 210 g, which is 44.2% of the feed size fraction weight. The iron grade in the magnetic product was 26.64%, which is higher than the iron grade in the feed size fraction (19.8%). The iron recovery in the magnetic fraction was 75.63%, which is lower than Experiment 3, but higher than Experiment 2. This indicates that using a low current (0.4 A) and a fine feed size fraction (-300 + 75 µm) resulted in a moderate concentration and efficiency of iron in the magnetic concentrates. It suggested that using a low current (0.4 A) and a fine feed size fraction (-300 + 75 µm) can be a good option for balancing both iron grade and recovery, as it may result in a reasonable quality and quantity of iron ore concentrates.

Based on the results, it is evident that the Frantz laboratory magnetic separator has enhanced the iron content in the concentrates compared to the raw feed fractions. The iron recovery varies from

68.3% to 90.17%, reflecting the efficiency of the magnetic separator in separating magnetic iron-bearing mineral particles. The iron grade varies from 20.84 % to 31.18 %, indicating the improved concentration of iron oxide mineral in the concentrates. These results reveal the impact of feed particle size and current on the performance of Frantz magnetic separator. These findings suggest that the optimal feed size fraction and current can significantly improve the magnetic separation process in enriching the iron content of the ore.

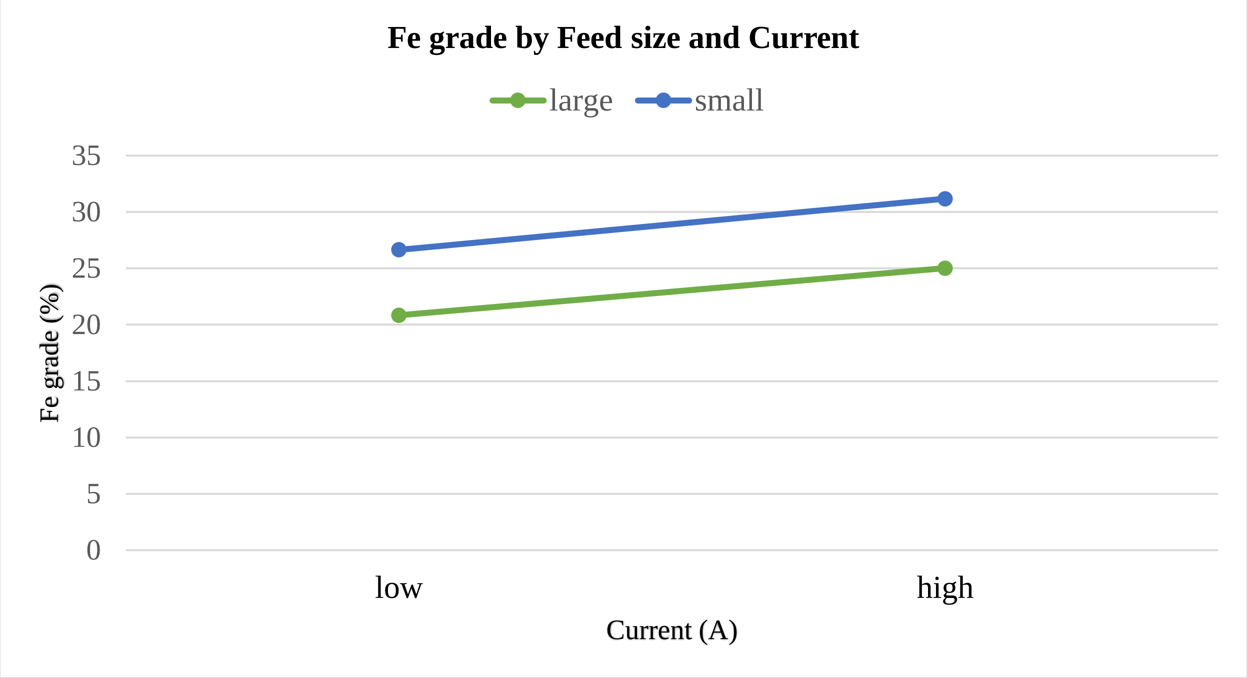

Figure 4. 2. Fe grade vs Feed size and Current

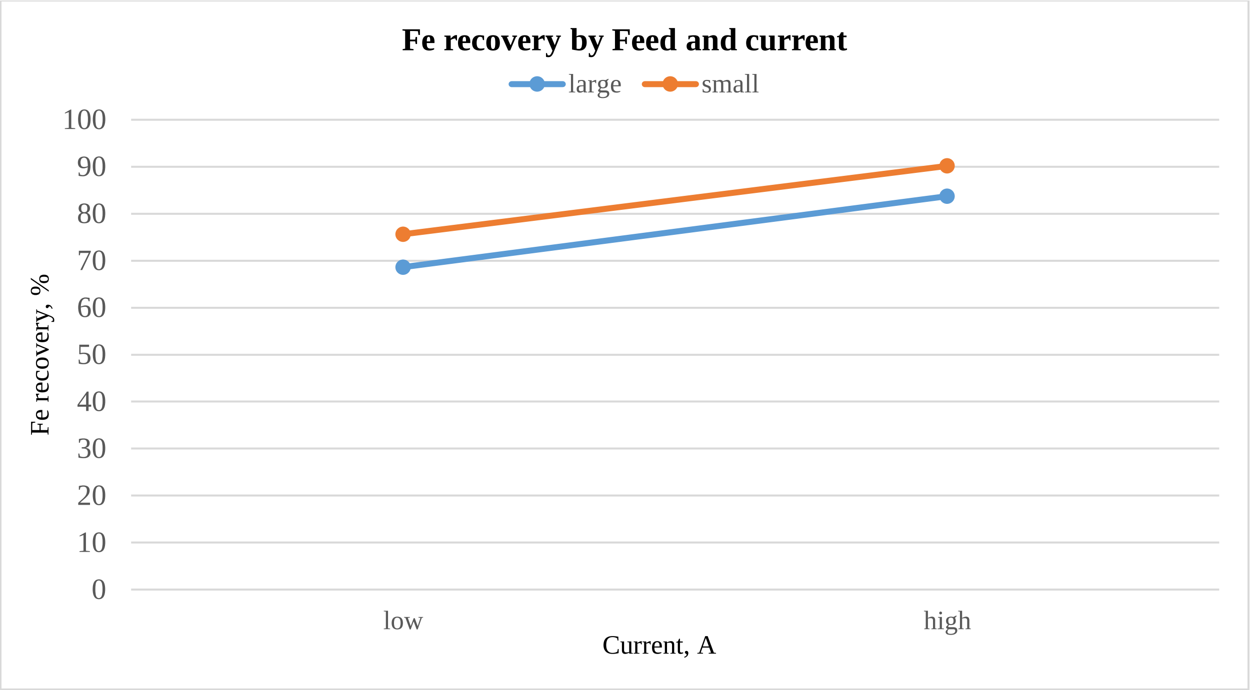

Figure 4. 3. Fe recovery vs Feed size and Current

The choice of optimal operating conditions, considering both iron recovery and grade, is crucial for maximizing the separation efficiency of the separator. The results from these experiments provide valuable insights into the relationship between feed size, current, and the measured iron (Fe) recovery and grade. Understanding these relationships allows for targeted adjustments of the process parameters to optimize iron recovery and grade, leading to improved overall separation performance. These results will be further analyzed and discussed to evaluate the main and interaction effects of variables on the product grade and recovery.

4.4. STATISTICAL ANALYSIS OF THE EXPERIMENTAL RESULTS

4.4.1. Experimental Design Analysis

In order to gain a comprehensive understanding of the effects of process parameter on the performance of the Frantz magnetic separation process, a Factorial modelling approach based on the Regular Two-Level design was employed. This approach, based on a two-level factorial design, allowed for systematic analysis of the effects of feed size (A) and current (B) on the process. These independent variables were chosen for their potential to significantly influence the Fe grade and the Fe recovery achieved from the Frantz laboratory magnetic separation process.

To ensure the validity of the results, each combination of tests was carried out in a randomized order. This helped to minimize the effect of un expected variability in the observed response due to extraneous factors. The experimental data obtained from the four experiments (shown in table) were analyzed using Design Expert v13.0.5 software. This facilitated the analysis of the data and provided insights in to the relationship between the factors and the response parameters.

4.4.2. Choosing Effects to Model

The effects of feed size and current on the Fe grade and recovery in the Frantz magnetic separation process were investigated using a Half-Normal plot and a Pareto chart. These tools were used to select the most suitable model for both responses among different alternatives, such as the main effects model and the interaction model. The Half-Normal plot displayed the standardized effects of the main effects (Factor A and B) and their interaction effect (AB) on the Fe grade and recovery. The red line separated the effects that were likely to be random noise from the effects that were significantly larger than the background noise.

The Pareto chart ranked the magnitude of the effects in descending order. The effects that crossed the threshold line were considered important and influential on the responses. Both tools indicated that the main effects model was the best fit for the data, as both feed size and current had significant and large effects on the Fe grade and recovery, while their interaction effect was small and insignificant. Therefore, the main effects model was able to capture the relationship between the feed size and current and the Fe grade and recovery in a simple and accurate manner.

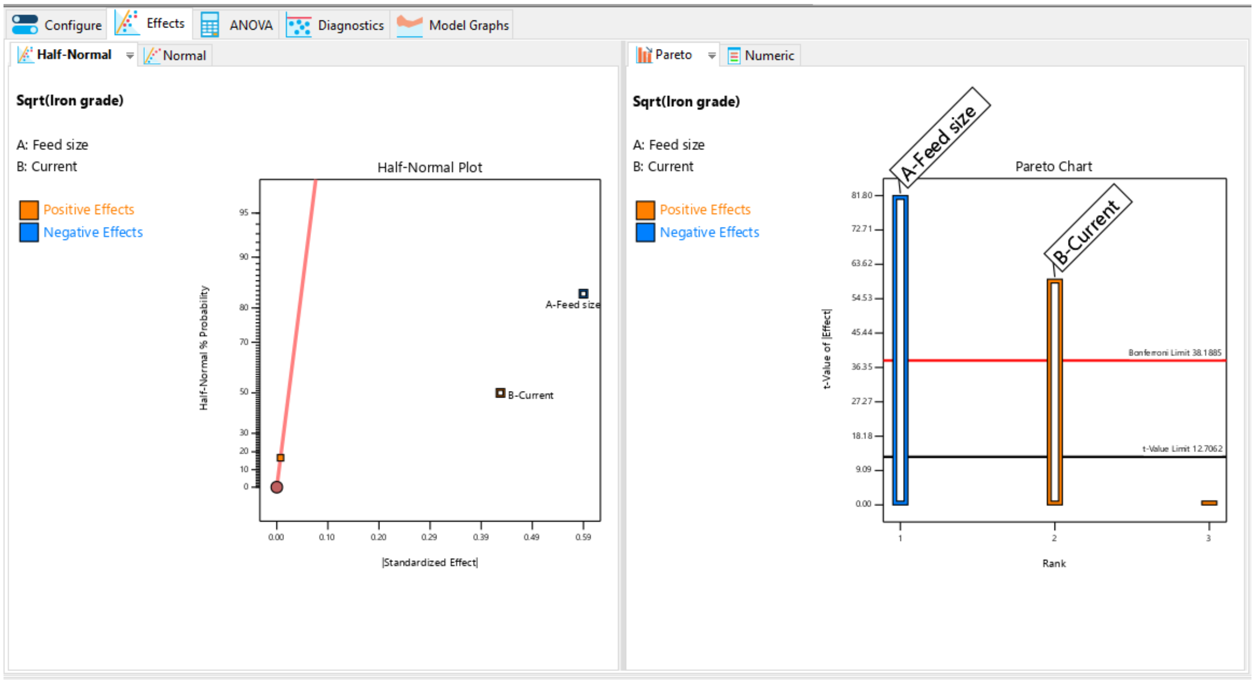

Figure 4. 4. Half-normal probability and Pareto plts in Design-Expert for Fe grade

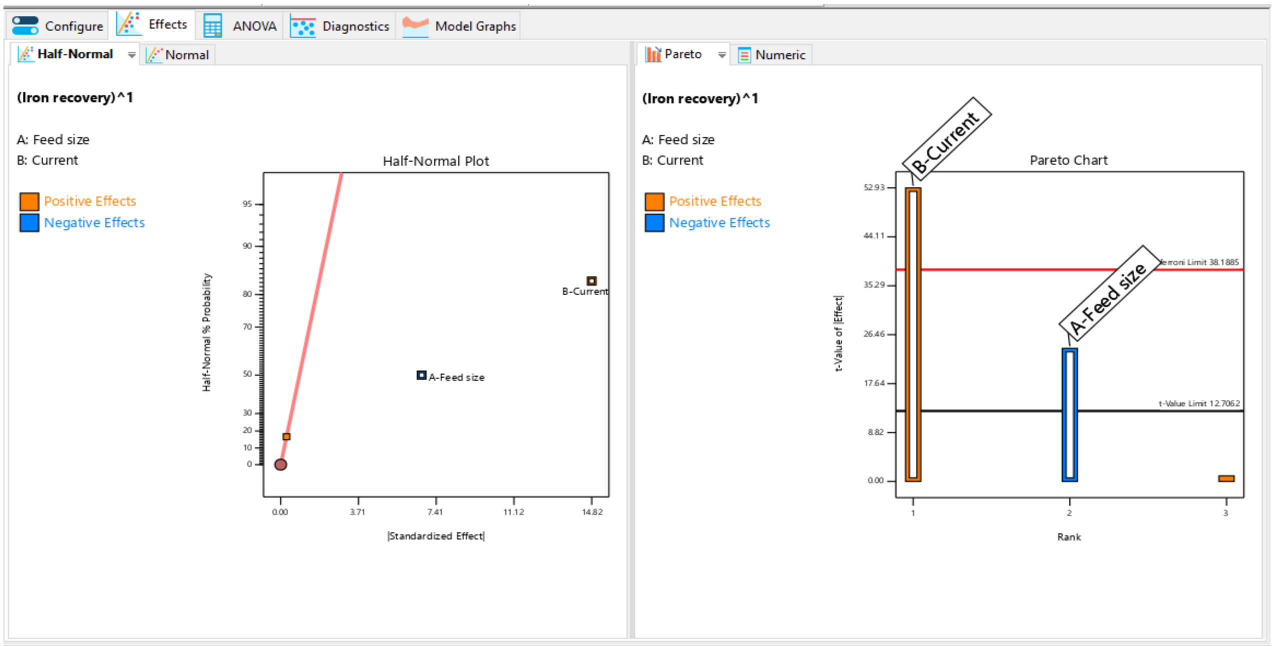

Figure 4. 5. Half-normalprobability and Pareto plots for Fe recovery

4.4.3. Analysis of Variance (ANOVA)

ANOVA, or analysis of variance, is a statistical method that tests the significance of the effects of one or more factors on one or more responses. It compares the variation within each group of observations to the variation between different groups of observations. It can be used to determine whether the differences between the means of the groups are due to random chance or due to the influence of the factors.

In this project work, ANOVA was used to analyze the effects of feed size and current on the iron grade and recovery in the Frantz magnetic separation process. The feed size and current were considered as two independent factors, each with two levels: -500+75 µm and -300+75 µm for feed size, and 0.4 A and 0.8 A for current. The iron grade and recovery were considered as two dependent responses, measured as percentages. A 2x2 factorial design was employed, resulting in four experimental runs with different combinations of feed size and current.

To test the statistical significance of the effects of the factors on the response, F-value and p-value in ANOVA were determined. The P values were used as a tool to check the significance of the factors, and to interpret the results for each factor. The larger the magnitude of F-value, and the smaller the magnitude of p-values, the higher the factors have a significant effect on the response.

P-values less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant. In this case, main effect model has a smaller p-value <0.0099 and 0.0172 for both responses Fe grade and recovery, respectively, which is less than 0.05 and the model F-value of 5125.13 and 1688.72 indicates the model is significant. In case for Fe grade, there is only a 0.99% chance that an F-value this large could occur due to noise, and only a 1.72% chance that an F-value this large could occur due to noise for the response Fe recovery.

As the results of the analysis of variance of the main effect model on the Table 4.4 and 4.6 revealed, A, B are significant model terms, i.e., the individual effects of feed size (A) and current (B) shows a significant influence on the response of iron grade and recovery value.

Table 4.4.ANOVA for Fe grade

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	0.5317	2	0.2659	5125.13	0.0099	Significant
A-Feed size	0.3470	1	0.3470	6690.48	0.0078	
B-Current	0.1847	1	0.1847	3559.78	0.0107	
Residual	0.0001	1	0.0001			
Cor Total	0.5318	3				

Factor coding is Coded. Sum of squares is Type III - Partial

Table 4.5. Fit Model Statistics for Fe grade

Std. Dev.	**0.0072**	R^2	**0.9999**
Mean	5.08	**Adjusted R^2**	0.9997
C.V. %	0.1418	**Predicted R^2**	0.9984
		Adeq Precision	163.3431

The Predicted R^2 of 0.9984 for the Fe grade response is in reasonable agreement with the Adjusted R^2 of 0.9997; i.e. the difference is less than 0.2. This indicates that the predicted values are closer to experimental data and the main effect model could represent the system for the given experimental domain. The closer the R^2 value to unity, the stronger the model and the better it predicts the response. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 163.343 indicates an adequate signal. This model can be used to navigate the design space. A lower value of coefficient of variation, C. V= 0.1418 % indicates the precision with which the experiments were conducted.

Table 4. 6. ANOVA for Fe recovery

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	264.79	2	132.40	1688.72	0.0172	Significant
A-Feed size	45.16	1	45.16	576.00	0.0265	
B-Current	219.63	1	219.63	2801.43	0.0120	
Residual	0.0784	1	0.0784			
Cor Total	264.87	3				

Factor coding is Coded. Sum of squares is Type III – Partial

Table 4.7. Fit Model Statistics for Fe recovery

Std. Dev.	**0.2800**	R^2	**0.9997**
Mean	79.54	**Adjusted R^2**	0.9991
C.V. %	0.3520	**Predicted R^2**	0.9953
		Adeq Precision	88.8295

For the second response Fe recovery, the Predicted R^2 of 0.9953 is in reasonable agreement with the Adjusted R^2 of 0.9991; i.e. the difference is less than 0.2. This also indicates that the predicted values are closer to experimental data and the chosen model (Factor A and B) could represent the system for the given experimental domain. The closer the R^2 value to unity, the stronger the model and the better it predicts the response. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 88.829 indicates an adequate signal. This model can be used to navigate the design space. A lower value of coefficient of variation, C. V= 0.3520 % indicates the precision with which the experiments were conducted.

Final Equation in Terms of Coded Factors: -

The model equation was developed to show the correlation between the process variables and percentage of iron grade and recovery.

$$\text{Iron grade} = +5.0781-0.294554 * A + 0.214856 * B \quad (2)$$

$$\text{Iron recovery} = +79.54-3.36 * A + 7.41 * B \quad (3)$$

Whereas: A is the Feed particle size (µm), and B is the Current (A).

The equation in terms of coded factors can be used to make predictions about the iron grade and recovery for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

4.4.3.1. Main effect of individual variables on the level of iron grade and recovery

The ANOVA results indicated that the main effect of feed size has a significant effect on both the iron grade and recovery of the Bikilal iron ore. This finding aligns with previous research and highlights the importance of particle size in the magnetic separation process. The particle size directly influences the surface area available for magnetic interaction, thus affecting the efficiency of separation. In general, smaller particle sizes tend to exhibit better separation performance. This is because smaller particles provide a larger surface area for magnetic interaction, increasing the chances of effective separation. Therefore, optimizing the feed size fraction by reducing the particle size can lead to improved iron grade and recovery. It is worth noting that there may be an optimal particle size range specific to the Bikilal iron ore, which could be further explored in future studies.

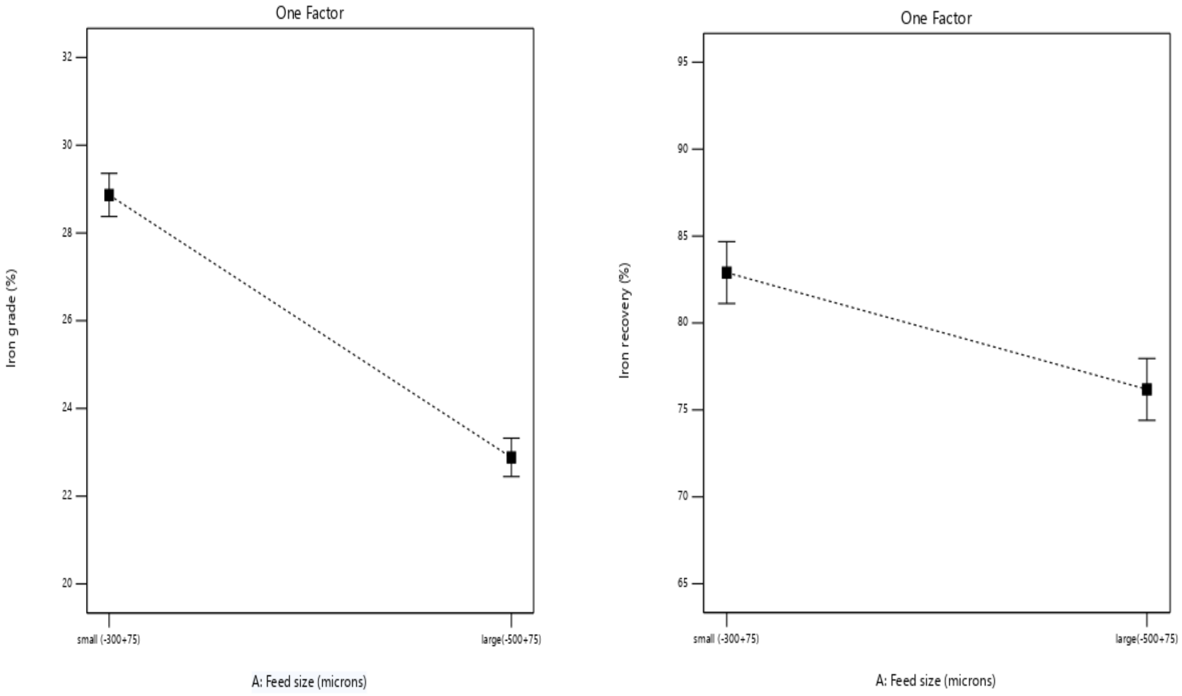

Figure 4. 6. Effect of Feed size on Fe grade and recovery

The ANOVA results also showed that the current parameter has a significant effect on the grade and recovery. This suggests that magnetic field intensity, controlled by the current parameter, plays a crucial role in the magnetic separation process. Magnetic field intensity affects the force exerted on the magnetic particles and determines their separation efficiency. By adjusting the magnetic field intensity, it is possible to enhance the separation performance. Higher magnetic field intensities can increase the force acting on the magnetic particles, improving their capture and separation. However, it is essential to strike a balance as excessively high magnetic field intensities can lead to undesired effects, such as entrainment of non-magnetic particles or loss of valuable magnetic minerals.

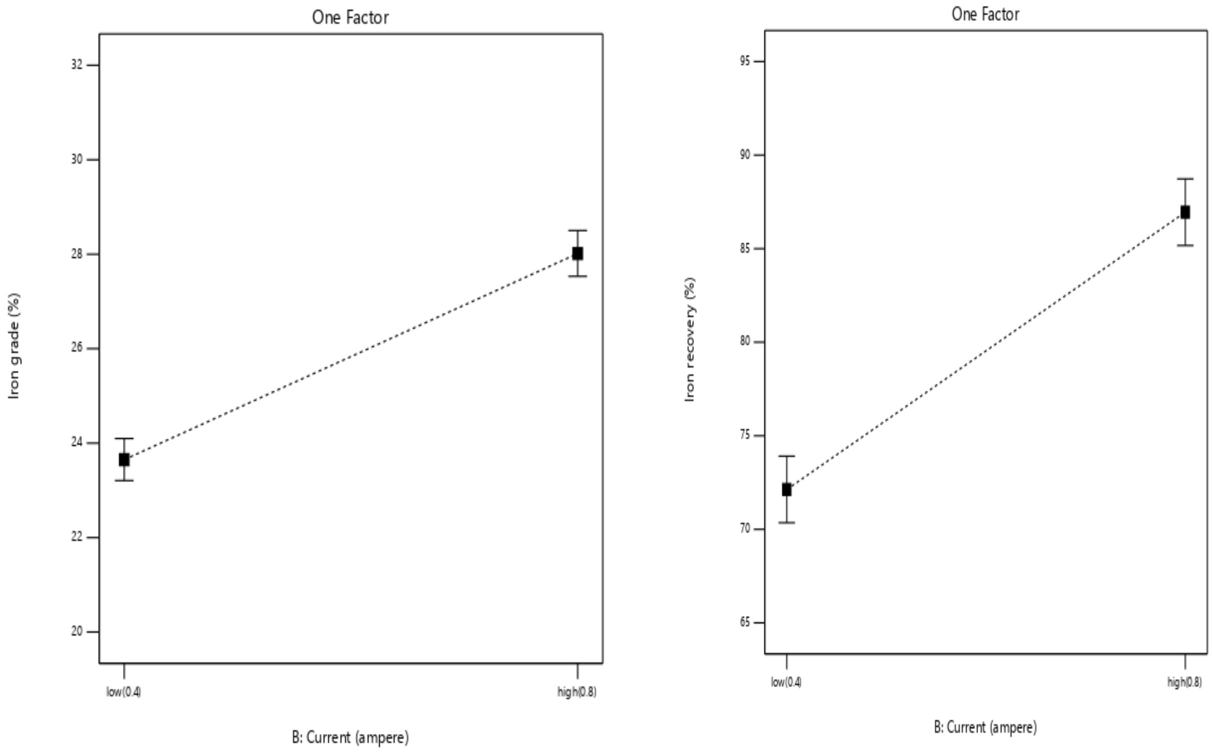

Figure 4. 7. Effect of Current on Fe grade and recovery

The results also indicated from the above figures, the iron grade and recovery increased with increasing current (0.8A) and decreasing feed size fraction (-300+75 µm). This can be explained by the fact that higher current produces higher magnetic field intensity, which enhances the magnetic force on the particles. Smaller feed size fraction reduces the particle-particle interactions and increases the surface area to volume ratio, which improves the magnetic susceptibility of the particles. The results of this study are consistent with some previous studies that have investigated the effects of particle size and current on the magnetic separation performance of different iron ores. For example, Sis et al. (2013) found that the iron grade and recovery of low-grade hematite ore increased with decreasing particle size up to -150+20 µm using wet high-intensity magnetic separation (H.T readings of 1.8 Tesla).

4.4.4. Optimization of Iron Recovery and Grade

The optimization of iron recovery and grade is crucial in maximizing the efficiency of the magnetic separation process for upgrading the iron content of the Bikilal iron ore. The statistical analysis performed using Design Expert software provided valuable insights into the optimal conditions for achieving the highest iron recovery and grade.

Based on the significant factors identified in the ANOVA, a Numerical optimization tool was employed to determine the optimal combination of categoric factor levels. The objective was to maximize both iron recovery and grade simultaneously, while satisfying any desirability or constraints functions. The numerical optimizer analysis suggested that the ideal conditions for maximizing iron recovery and grade were obtained with a -300 + 75 µm feed size fraction and a 0.8 A current. These conditions yielded an estimated iron recovery of 90.17% and an iron grade of 31.18%. To validate the optimized conditions, a confirmation experiment was conducted under the recommended settings. The results of the confirmation experiment closely aligned with the predicted values, providing confidence in the accuracy and reliability of the optimization process. The achievement of higher iron recovery and grade at the optimized conditions highlights the importance of selecting the appropriate feed size fraction and current for the magnetic separation process.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The present study aimed to investigate the potential for upgrading the iron grade of Bikilal iron ore using magnetic separation with the Frantz Magnetic Laboratory Separator. The study also aimed to investigate the effects of Feed size and Current on the efficiency of magnetic separation. The research question was: What are the effects of feed size fraction and current on the iron recovery and grade of Bikilal iron ore using magnetic separation with the FMLS?

Through experimental investigation and statistical analysis, the following conclusions can be drawn.

- The chemical analysis of the Bikilal iron ore revealed that its composed of 19.50 % Fe_2O_3. The previous mineralogical analysis of the ore indicated that, the dominant mineral phases present in the Fe_2O_3 were found to be magnetite followed by ilmenite. Additionally, the study identified the presence of quartz (45.66% SiO_2) and kaolinite (9.96% Al_2O_3) as impurities in the ore.

- The magnetic separation process using the Frantz Magnetic Laboratory Separator was effective at cobbing stage in separating the magnetic materials from the non-magnetic materials in the Bikilal iron ore. The magnetic separation process using the FMLS was able to separate and increase the % Fe_2O_3 by 11.38 wt. %, and recover 91.2% of the magnetic materials in the concentrate compared with the feed sample. This is a satisfactory improvement for the rougher stage preliminary magnetic concentration compared to studies that used other magnetic separator, which increased a 20 wt.% Fe.

- The statistical analysis of the experimental data revealed that both the feed size fraction and current had a significant impact on iron recovery and grade. The optimal conditions for maximizing iron recovery and grade were identified as a -300 + 75 µm feed size and a 0.8A current, which yielded an estimated iron recovery and grade of 90.2& and 31.2 % respectively.

In general, the study has some implications for the magnetic separation process design and optimization. It demonstrates that the Frantz® Low Field Control Model LFC-2 is a useful accessory for separating ferromagnetic materials according to differences in their magnetic properties. It also shows that the feed size fraction and current are important parameters that affect the magnetic separation performance, and that they should be carefully selected and controlled. The study also provides some insights into the trends and correlation among the factors and responses, which can help to understand the underlying mechanisms of the magnetic separation process.

5.2. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are suggested for future research.

- Further investigation into the mineralogical and chemical characteristics of the Bikilal iron ore should be conducted to gain a more comprehensive understanding of its composition and potential beneficiation strategies. This will help to identify other valuable minerals that can be recovered from the Bikilal iron ore such as titanium and phosphorous.
- The optimization process can be further refined by considering and investigating additional process parameters and constraints, such as feed rate, tilt angle, and residence time. This will help to ensure that the results are robust and can be applied to other scenarios.
- The sample size should be increased to explore the exact operating conditions required for optimal performance of the Frantz laboratory magnetic separator. This will ensure the results are representative of the entire ore deposits.
- Other aspects such as environmental and economic considerations should also be considered to further utilize Bikilal iron ore at pilot and industrial scale. This will help to ensure that the process is sustainable and economically viable.
- Several stages (cleaning and scavenging) should be used to increase the recovery of valuable minerals and reduce waste.
- A combination of tests such as inverse cationic flotation followed by magnetic separation can be used to reduce the level of impurities to an acceptable level in concentrating the

desired iron mineral for the downstream stream metal iron extraction process. This will offer enhanced results for upgrading the iron grade of the Bikilal iron ore.

- Overall, this study provides valuable insights into the beneficiation of the Bikilal iron ore and lays the foundation for further research and development in this field. The results and recommendations contribute to the sustainable utilization of mineral resources and the economic growth of the region.

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