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Beneficiation of Balochistan Magnetic Sand through the Magnetic Separation Technique and Effect of Particle Size for Iron Enrichment

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Abstract

The present study aims to develop an economic beneficiation process to promote the utilization of indigenous low grade magnetic sand from Balochistan for iron production. A low-intensity magnetic separator (LIMS) was employed to upgrade raw materials and produce iron concentrate for the steel and iron industries, thereby contributing to reducing iron imports in Pakistan. The effect of particle size and processing medium (dry and wet conditions) on iron (Fe) recovery. Under dry conditions, the optimum performance was obtained for the −150 + 200 mesh particle size fraction, yielding a concentrate containing 70.0% Fe and 1.75% silica (SiO_2) with a weight recovery of 44.0% and an Fe recovery of 94.21%. In contrast, under wet magnetic separation, the optimum fraction −200 produced a concentrate containing 64.40% Fe and 4.25% SiO_2 with a weight recovery of 47.54% and an Fe recovery of 93.65%. The results demonstrate that dry magnetic separation is more effective than wet processing for upgrading the studied magnetic sand. The study highlights the potential of Balochistan magnetic sand as a viable local resource for iron enrichment through a simple and cost-effective magnetic separation technique.

Keywords

Balochistan, Beneficiation, Magnetic Sand, Low Intensity Magnetic Separator, Iron Concentrate

1. Introduction

Iron ore is an essential natural resource for industrial development and a primary raw material for the production of steel and different iron based industries [1].

For the economic growth of the country, iron and steel industries play a vital role. These industries have vast applications in different sectors, especially construction, automobile, shipment, machinery, tools for mining, agriculture, military and chemical.

Pakistan's estimated iron ore reserves are approximately 1.4 billion tons. In Punjab province, Chiniot-Rajoa Saddat (Chiniot), there are 27.46 million tons with low to high iron content (45% - 64%), Kalabagh (Mainwali), 300 - 350 million tons having 30% - 34% iron and Dera Ghazi Khan has 268.3 million tons with 30-37% of iron content. In KP, 6.5 million tons contain 30% - 50% iron [2]. Balochistan is the largest province of Pakistan by area and is blessed with diverse metallic and non-metallic minerals and coal resources. Iron ore reserves (335 million tons estimated by GSP) are present at different localities in Balochistan.

Iron ores mainly occurred as (a) hematite, a type iron oxide (Fe_2O_3) having 70% iron and 30% oxygen (b) limonite ferric hydroxide (mFe_2OnH_2O) contains 62% iron content and 11% water (c) siderite in the form of ferrous carbonate ($FeCO_3$) contains 55.8% iron and 48% oxygen (d) magnetite (Fe_3O_4) is a compound of Fe_2O_3 and FeO and contain 72.14% of iron and 27.60% oxygen [3]. In Padag area of Chagai district, metamorphic and igneous magnetite formed octahedral or granular masses in ultramafic and mafic rocks in the form of iron oxide(Fe_3O_4).

Available data showed that Pakistan largely depends on importing raw materials for steel industry. Rabab *et al.* analyzed the extraction of iron method for the period of 2005 to 2020 and reported that Pakistan extracted 2,057 Mt of iron ore in this period. It is further reported that Pakistan imports iron from China, Japan and United Arab Emirates around 13.14%, 6.86% and 6.24%, respectively, to meet its requirements [4]. During the year 2020-2021, imports of steel scrap were USD 1.9 billion in value and 4.7 million tons in volume. Contrary to imports, if Pakistan substitutes imports with local production, it can save around 2 billion USD on an annual basis [5].

1.1. Iron Ore Reserves in Balochistan

According to the geological survey of Pakistan and available data regarding iron ore reserves [2] are as follows in Table 1.

Table 1. Reserves of iron ore in Balochistan, Pakistan.

Locality/Area/District	Estimated Reserves (million tonnes)	Iron %
Chigendik, Amir Chah, Pachin Koh, Jol khand Chilghazi, chagai district	**85**	**20% - 60%** Magnetite (Fe_3O_4) & Hematite (Fe_2O_3)
Dilband district kalat	**250**	35 - 45 sedimentary hematite (Fe_2O_3)
Uthal, district lasbela	**Reserves not estimated**	**45%** Magnetite (Fe_3O_4) & Hematite (Fe_2O_3)

It is reported that in the financial year of 2018, more than 5,000 operational mines and around 50,000 small and medium enterprises were present in Pakistan with more than 140,000 employees (0.23% of the total country's employed population) [6]. Magnetite sand/ore is the most magnetic naturally occurring mineral that occurs in different parts of the world.

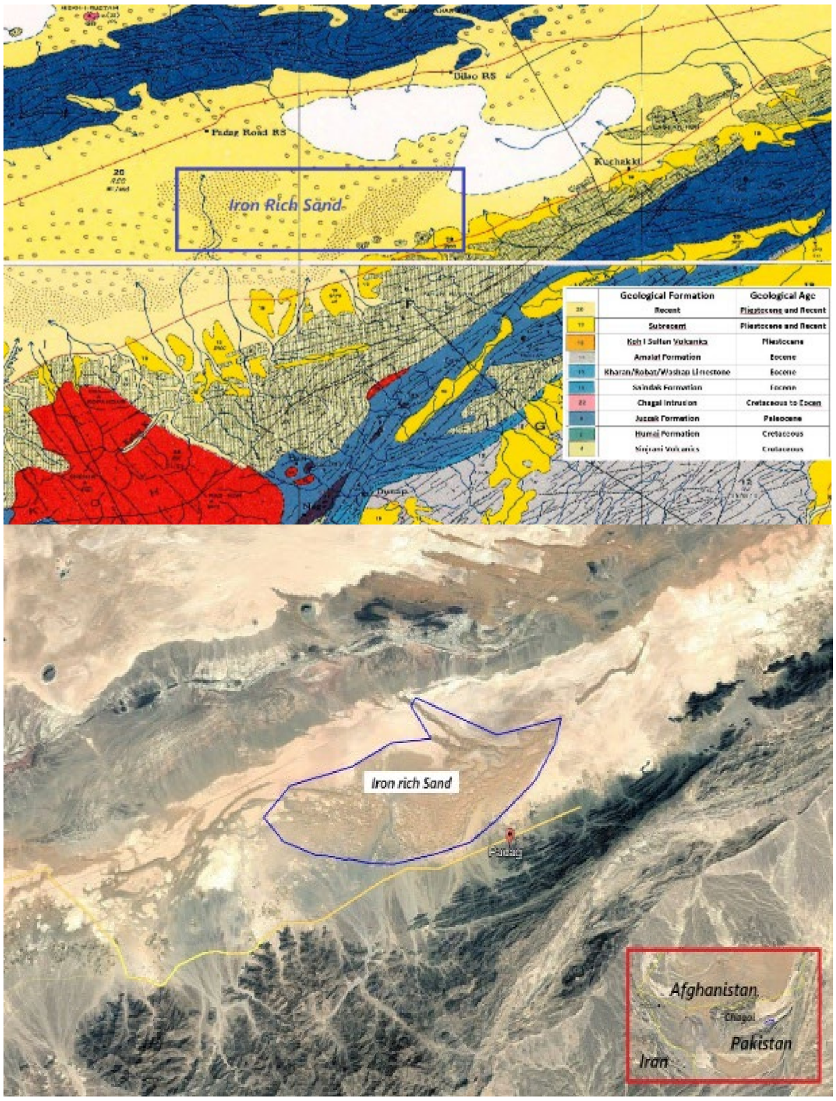


Figure 1. Geological (up) and satellite (down) map of Padag area district, Chaghai, Balochistan.

In Balochistan, an area of Padag is a mountainous and desert plain zone, located in the district Chagai, approximately coordinates **29.00305˚N, 65.31538˚E**. Geological map (up) and satellite image (down) of magnetite sand/ore are shown in Figure 1.

1.2. Production of Iron Ore in Pakistan

Pakistan holds around 1.4 billion tons of iron ore [2], whereas year-wise production of iron ore from 2017 to 2021 is shown in Figure 2. The reported differences in mining of iron ore between 2017 to 2021 and 2020 to 2021 are 60.60% and 40.44%, respectively [7].

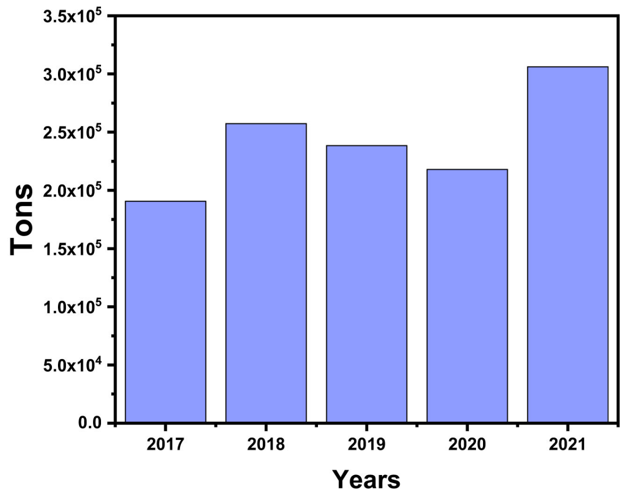


Figure 2. Mining of iron ore in Pakistan from 2017 to 2021.

1.3. Worldwide Crude Steel Production

In 2019 top ten steel-producing countries were mentioned by the World Steel Association [8]. Pakistan contributed only 0.18% in world steel production, ranked 39th out of 50 countries as shown in Figure 3.

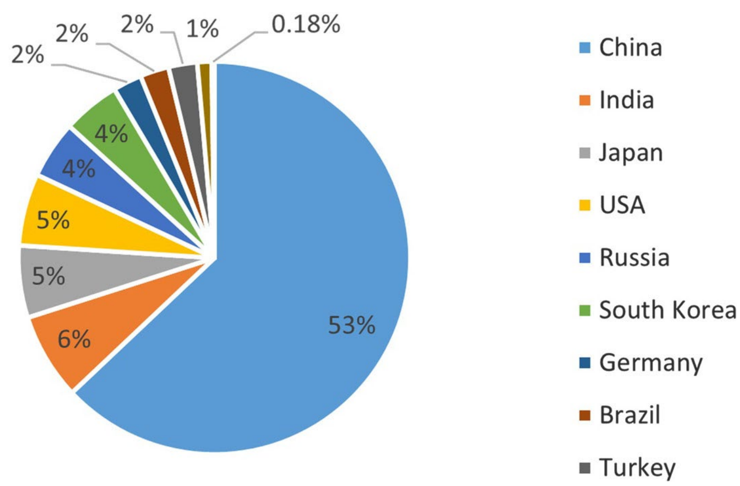


Figure 3. Worldwide crude steel production percentage (2019).

1.4. Different Iron Separation/Beneficiation Techniques

Different beneficiation techniques are used worldwide [9] [10] for low-grade iron ore, one of them is magnetic Separation. This separation is based on differences in the magnetic susceptibilities of minerals. Magnetic minerals (e.g., magnetite, pyrrhotite, ilmenite) are attracted to the magnetic field as concentrate, while non-magnetic minerals (e.g., quartz, feldspar, calcite) are left as tailing. Two types of magnetic separators are used: one is a high-intensity magnetic separator (HIMS) with a magnetic field up to 20,000 gauss, and the other is a low-intensity magnetic separator (LIMS) with a magnetic field of 1000 - 3000 gauss [11]. Second separation technique is the shaking table depends on gravity differences and differential movement of particles along an inclined, shaking surface. Particles of higher density move in a different path than lighter ones [12]. A slurry of ground ore is fed onto a table with riffles. The table shakes in a longitudinal motion while water flows transversely. Shaking table technique produces a high-grade concentrate, environmentally friendly (no chemicals) involved in it. Froth flotation is another physicochemical separation technique [13] used mainly for the beneficiation of ores, especially sulfide and oxide minerals. The process depends on the fact that certain minerals attach preferentially to air bubbles due to their hydrophobic surfaces [14], while others remain in the aqueous phase. When air is passed through a mixture of finely ground ore and water containing suitable reagents, the hydrophobic particles rise to the surface with bubbles, forming a froth, which is collected as a concentrate. Schematic detail of magnetic separation, shaking table and froth flotation technique is shown in **Figure 4**.

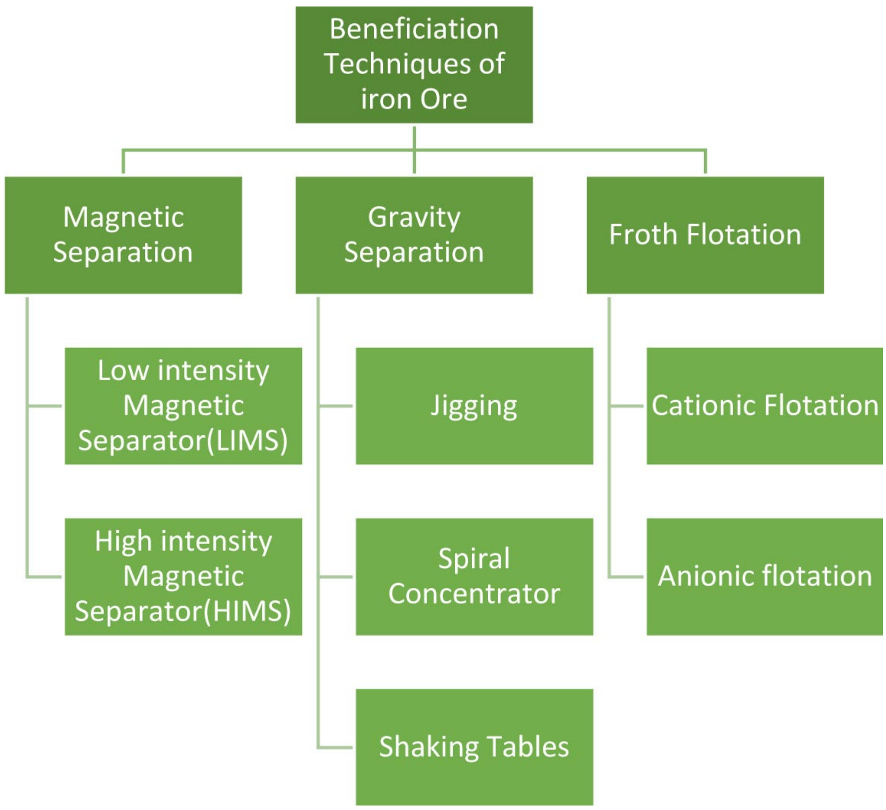


Figure 4. Schematic diagram for beneficiation techniques.

Magnetite sand/ore to obtain the concentrate and tailing from the head sample. This LIMS is an easy, non-destructive and eco-friendly technique for iron containing minerals/ores.

Although significant work has been reported on beneficiation of low grade iron ores using magnetic, gravity, and floatation techniques, limited information is available regarding the beneficiation behavior of magnetic sand deposits from Balochistan, Pakistan. Furthermore, these indigeneous magnetic bearing sands dependent on the particle size enrichment have not been investigated systematically. Therefore, present study aims to evaluate the effect of particle size on the beneficiation efficiency of Balochistan magnetic sand using low intensity magnetic separator (LIMS) technique was used for the beneficiation of dry test and wet test. Iron recoveries (R) were calculated by following equation [15].

$$R = \frac{C \times c}{F \times f} \times 100$$

Here F and C represent feed and concentrate, whereas f and c represent Fe grades of feed and concentrate, respectively.

2. Methodology

2.1. Sample Preparation

The Magnetite sand/ore sample was arranged from an area of Padag, District Chagai, Balochistan, with approximate coordinates **29.00305˚N, 65.31538˚E** and brought to Mineral Technology Center (MTC) PCSIR Lab, Quetta for R&D in house project. To prepare 20 Kg composite of magnetite ore, samples were collected at a depth of 0 - 1 meter. Twenty individual increments of approximately 1kg each were collected from different points and combined to obtain a 20 Kg composite sample. The composite /head sample was in the form of granular sand. Mixing, coining and quartering, followed by a cup mill were done for X-Ray Diffractometer (XRD) and chemical analysis.

2.2. Chemical Analysis of Head Sample

Conventional gravimetric, volumetric and instrumental methods were used for the determination of chemicals. Silica (SiO_2) and associated minerals contents in head samples, concentrate, and tailing. Determination of iron content was done by using potassium dichromate as a standard solution in redox titration (ASTM E-246-01), EDTA titration method was used for aluminium (Al) analysis (ASTM E738-05), Jenway Limited (England-PFP7) flame photometer was used for potassium and sodium analysis [14].

2.3. Particle Size/Sieve Analysis

500 g of head sample (in granule form) was used for sieve analysis by using Octagon 200, Eondecotts England sieve shaker. Six different mesh numbers were obtained and used for the experiment. Step-wise depiction of the procedure followed for the beneficiation process of magnetite sand/ore by using low intensity magnetic separator (LIMS) is shown in **Figure 5(a)-(g)**.

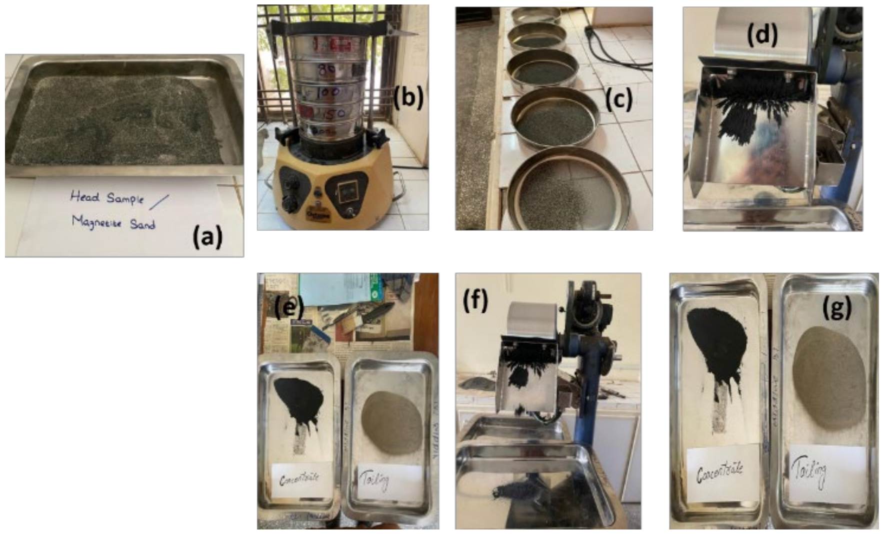


Figure 5. Depiction of methodology from (a) to (g).

Flow sheet diagram for the Beneficiation of magnetite sand/Ore of district Chaghai, Balochistan, is shown in Figure 6.

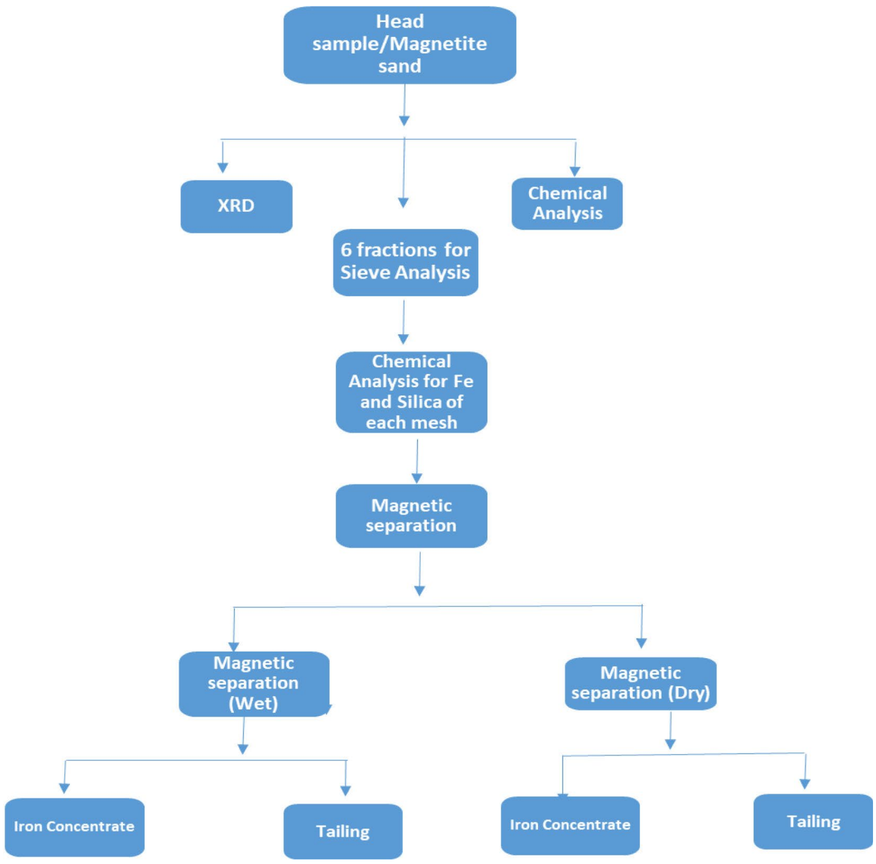


Figure 6. Flow sheet diagram of beneficiation process.

Optimum conditions applied for dry and wet tests are shown in Table 2.

Table 2. Optimum conditions for separation tests (dry & wet).

S.No	Parameter	Dry Separation	Wet Separation
01	Drum Speed	40 r/min	40 r/min
02	Magnetic field intensity	1200 gauss	1200 gauss
03	Feed rate	100 g/min	100 g/min
04	Feed pulp density	N/A	25% Solids
05	water flow rate	N/A	500 mL/min

3. Results and Discussion

3.1. XRD Analysis

Mineralogy of the head raw sample was carried out by using XRD (Equinox 2000 Thermo Fisher Scientific, USA instrument (CU Kα1)). Figure 7 shows the XRD patterns of the sample. The presence of peaks at (311), (533) and (731) planes corresponds to the magnetite in the samples with higher concentration; however, intensity peaks at (101), (102) and (112) correspond to quartz/silica, as reported in the literature.

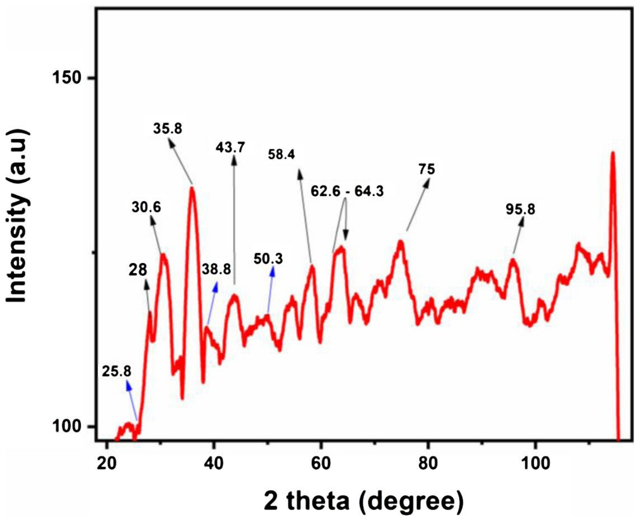


Figure 7. XRD pattern of the head sample.

Similarly, characteristic peaks of magnetite with hkl plane indices (as shown in Table 3) are well matched with JCPDS card numbers 46-1045, 05-0586, 19-0629, 33-0664 and 36-0426 [16] [17].

Table 3. XRD details of head sample.

2θ (Degrees)	hkl	Peak intensity
25.8	(101)	Low
28	(104)	Low
30.6	(220)	High

Continued

35.8	(311)	Most High
38.8	(102)	Low
43.7	(400)	Broad
50.3	(112)	Low
58.4	(511)	Medium
62.6 - 64.3	(440)	Broad
75	(533)	High
95.8	(731)	Medium

3.2. Chemical Analysis

Constituents present in the head sample are shown in **Table 4**.

Table 4. Chemical analysis of head sample.

S.No	Element	Percentage (%)
1	moisture	0.13
2	Loss on ignition	0.40
3	SiO_2	47.26
4	Fe	32.69
5	Al_2O_3	1.25
6	CaO	1.90
7	MgO	0.90
8	Na_2O	0.30
9	K_2O	0.28

3.3. Sieve Analysis

Table 5 shows the results of sieve analysis and **Figure 8** shows the graph between the mesh no and weight in percent of head sample. **Figure 9** shows the percentage retained and passed in different fractions/mesh sizes. **Figure 10** shows the distribution of iron (Fe) percentage and silica (SiO_2) percentage contents in different mesh sizes. It is observed that both Fe and SiO_2 contents are showing an inverse relation as mesh size was reduced. Fe showed its maximum content percentage (49.70) in −150 + 200 mesh whereas at the same mesh size SiO_2 showed minimum content percentage (26.02) in head sample.

Table 5. Sieve analysis.

Mesh No	Weight in (g)	Weight in (%)	Cumulative weight retained (%)	Cumulative weight Pass (%)
+50	24.10	4.82	4.82	95.18
−50 + 80	178.90	35.78	40.60	59.40

Continued

−80 + 100	81.70	16.34	56.94	43.06
−100 + 150	107.70	21.54	78.48	21.52
−150 + 200	35.60	7.12	85.60	14.40
−200	72.00	14.40	100	0.00

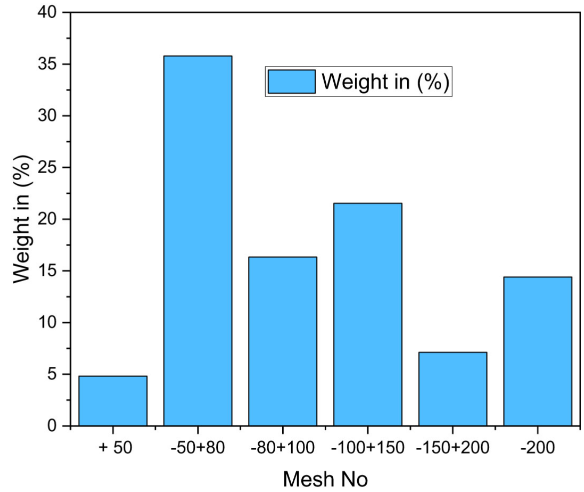


Figure 8. Weight in percentage of head sample.

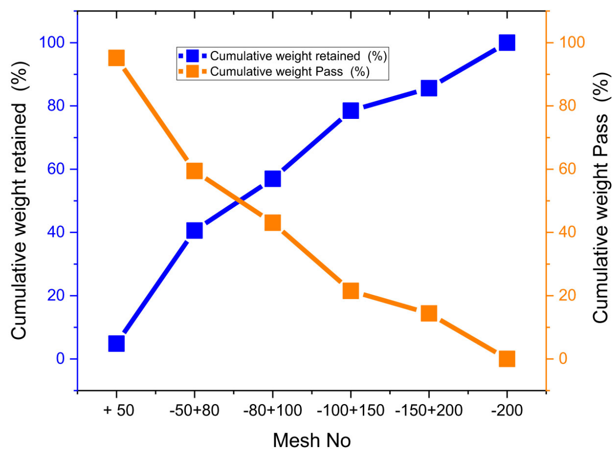


Figure 9. Cumulative weight (%) of head sample retained and passed through different mesh no.

3.4. Beneficiation by Magnetic Separation for Fe Concentrate

On the basis of XRD, chemical analysis and particle size, it is observed that the head sample is mainly consisted of Magnetite (Fe_3O_4). For the removal of gangue, magnetic separator technique was used on different mesh sizes. In present research low-intensity magnetic separator was applied for ferromagnetic minerals like magnetite and paramagnetic minerals like hematite [18]. Head sample analysis depicted in Table 3 reveals that it is mainly composed of two major constituents: iron (Fe) 32.69% and silica (SiO_2) 47.26%.

Dry and wet tests were performed, as reported in literature [18], to separate out Fe from SiO_2 via five different mesh numbers through Lab scale single drum magnetic separator (WS 201 blue Ribbon). Results obtained by using mesh size +50 exhibited the lowest Fe contents (11.50%) with highest SiO_2 contents (69.20%) among the investigated size fraction, therefore, this fraction was excluded from subsequent separation test. For each test, 1000 g of sample was used to obtain concentrate and tailing. Magnetic drum rotational speed was kept constant for both dry and wet separation tests as shown in **Table 2**. **Figure 10** showed the distribution of Fe and SiO_2 percentages in six different mesh size trials conducted on magnetic separator.

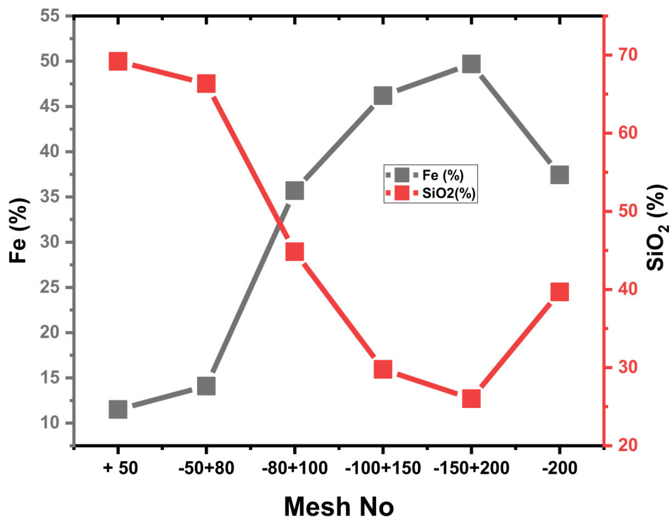


Figure 10. Iron (Fe) and Silica (SiO_2) percentages in different mesh sizes.

3.4.1. Dry Test

Head sample having 32.69% Fe content and 47.26% of SiO_2 was screened into five different particle size/friction using a series of mesh sizes. **Table 6** represents the concentrate and tailing results obtained at different mesh sizes for the yield of Fe and SiO_2 concentration and tailing fractions by using a dry single drum magnetic separator. It is clearly observed, Fe was around 47% with a higher fraction of SiO_2 (30%) at coarser size (−50 + 80), as the size decreased and fining, the Fe (%) recovery increased and reached a maximum value (70%) with mesh size −150 + 200 with the least SiO_2 impurities. However, this trend deviates at the fine mesh size (−200), indicating that at the fine size, magnetic efficacy is decreased, as shown in **Figure 11(up)**.

Table 6. Dry magnetic separation.

S.No	Mesh No	Total weight (g)	Concentrate (g)		Tailing (g)		Fe Recovery (%)	Weight Recovery (%)
			Fe %	SiO_2 %	Fe %	SiO_2 %		
1	−50 + 80	1000	309		691		44.33	30.90
			46.9	30.44	1.4	89.02		

Continued

2	−80 + 100	1000	**475**		**525**		92.55	47.50
			63.7	8.25	1.5	87.14		
3	−100 + 150	1000	**450**		**550**		93.46	45.00
			67.9	4.5	1.61	89.24		
4	−150 + 200	1000	**440**		**560**		94.21	44.00
			70	1.75	3.08	83.8		
5	−200	1000	**450**		**550**		89.06	45.00
			64.7	5.7	5.04	74.86		

Similarly, tailing percentage represents the efficient effect of magnetic separator and showed that as the mesh size was getting finer, the SiO_2 tailing percentage was increasing and maximum Fe was separating from the gangue mineral. However, at the fine mesh size, the liberation of magnetic Fe from the non-magnetic SiO_2 was decreased as shown in Figure 11(down), which depicts that mesh size plays a very important role in the efficiency of dry magnetic separator and it shows the best results only for the optimal range that is around −150 + 200 mesh number. Enhanced liberation of magnetic selectivity and Fe enrichment is attributed to the improved magnetic separation performance at finer particle sizes. However, particle aggregation and entrainment effects reduce the efficiency at excessive size reduction.

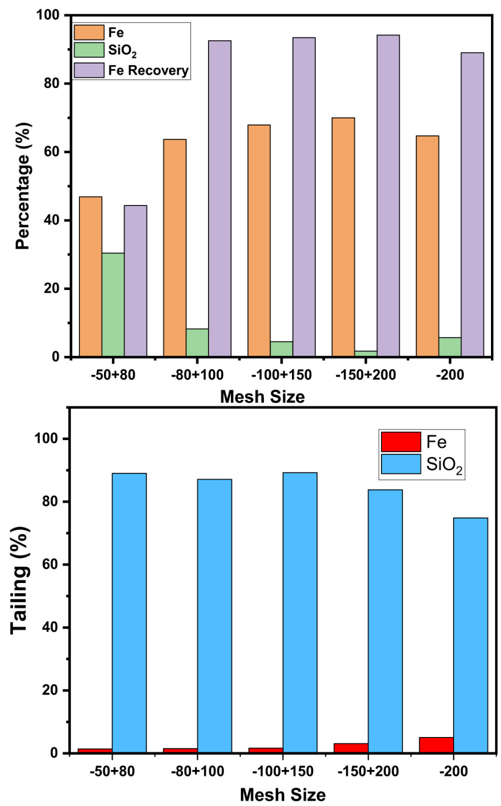


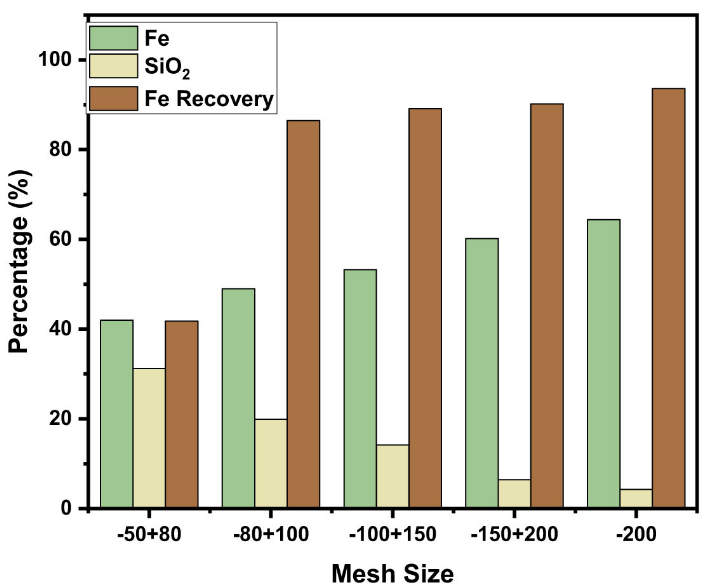
Figure 11. Concentrate percentages of iron (Fe), silica (SiO_2) and weight recovery (up) and tailing (down) based on different mesh sizes by dry magnetic separator technique.

3.4.2. Wet Test

Head sample having 32.69% Fe content and 47.26% of SiO_2 was screened into five different particle size/friction using a series of mesh sizes. Table 7 represents the results obtained at different mesh sizes for Fe % and SiO_2 % in concentrate and tailing fractions by using a wet single drum magnetic separator. It is seen that the concentration for Fe was around 42% with a higher fraction of SiO_2 (31%) at coarser size (−50 + 80) and the same trend continued as the size was decreasing and fining and reached a maximum value of 64.4 % with mesh size −200 and the least SiO_2 contents, as shown in Figure 12(up). Similarly, results obtained from tailing percentage with maximum rejection of non-magnetic SiO_2 from the gangue mineral by using wet magnetic separator are shown in Figure 12(down).

Table 7. Wet magnetic separation.

S.No	Mesh No	Total weight(g)	Concentrate(g)		Tailing (g)		Fe Recovery (%)	Weight Recovery (%)
			Fe %	SiO_2 %	Fe %	SiO_2 %		
1	−50 + 80	1000	**325.11**		**674.89**		41.77	32.51
			42	31.24	1.4	88.22		
2	−80 + 100	1000	**576.90**		**423.09**		86.47	57.69
			49	19.92	1.7	85.92		
3	−100 + 150	1000	**549.71**		**450.25**		89.12	54.97
			53.25	14.16	2.1	83.48		
4	−150 + 200	1000	**490**		**510**		90.23	49.00
			60.2	6.42	7.7	80.08		
5	−200	1000	**475.42**		**624.60**		93.65	47.54
			64.4	4.25	8.4	72.08		



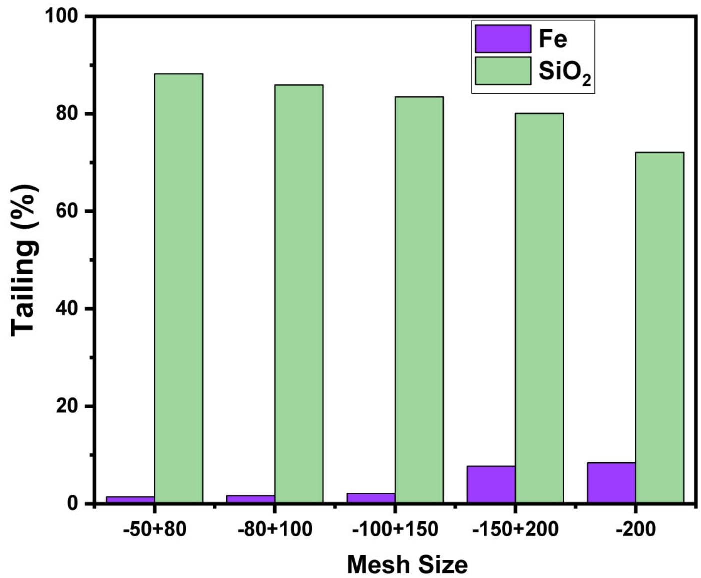


Figure 12. Wet Iron (Fe), silica (SiO_2) and weight recovery (up) and tailing (down) based on different mesh sizes.

On comparison with dry magnetic separator, it is observed that at the fine mesh size (−200), the efficiency of wet magnetic separator is decreased, as was the case in dry magnetic separator and overall, it is suggested that both dry and wet magnetic separators yield good results as the mesh size was decreased and declined at ultrafine particle size [15]. However, the Fe recovery percentage for wet magnetic separator showed an inverse trend with mesh size and continues to increase and reaching a maximum recovery (93.65%) at the fine (−200) mesh size as shown in **Figure 12(down)**. This shows that the separation efficiency is governed not only by particle size and magnetic susceptibility but also by slurry hydrodynamics. Presence of water enhances the reduction in mechanical entrainment and particle dispersion, resulting in improved rejection of non-magnetic gangue minerals.

The results obtained in present study are consistent with the literature reporting that the efficiency of magnetic separation of low grade iron ores are significantly influenced by the particle size. Sis *et al.* [18] reported that magnetic separation performance and concentrate grade were enhanced at finer particle sizes. Similarly, another group of researchers also reported that appropriate size reduction plays a vital role in the Fe recovery [10].

4. Conclusion

Investigation revealed that head sample was mainly composed of magnetite (Fe_3O_4) with major impurity/gangue silica (SiO_2) mineral and the amount of iron (Fe) present in the head sample was quite enough to exploit the magnetite sand/ore to achieve high to standard grade iron concentrate for commercial uses. Overall results obtained from magnetic separator technique showed that dry magnetic separator yielded superior performance over wet by achieving higher Fe (70%) content with low SiO_2 (1.75%) impurity in concentrate and significant Fe recovery (94.21%) at mesh size (−150 + 200). However, wet technique showed dominant results at fine mesh size (−200) with 64.40% Fe content and recovery (93.65%).

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Authors Contribution

Muhammad Aamir Raza and Khurram Shahzad initiated the research idea and develop overall research plan, Muhammad Aamir Raza, Nadia Khan and Bibi Seema conducted experimental analysis and data calculations and Dr. Farrukh Bashir and Muhammad Aamir Raza interpreted the data, and finalized the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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