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ORIGINAL ARTICLE

Feasible Beneficiation Studies to Enrich Grade and Recovery by Adopting Grinding Followed by Gravity and Magnetic Separation

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Abstract The recovery of Fe from an oversized sample in a spiral classifier upgrades a 55% Fe to 59% Fe output in a size range (− 3 mm + 150 µm). The output was subjected to fine grinding making it suitable for pellet plant. The ground fine ore was subjected to 2 processing routes: gravity concentration followed by magnetic separation. The tailing after gravity separation was subjected to magnetic separation with varying Gauss. One set of Fe enrichment was achieved in the concentrate after gravity separation and in the mag part of magnetic separator. The overall concentrate was 61.38% Fe, 4.53% SiO_2, and 2.97% Al_2O_3, with an yield of 83.45%. The Fe recovery was 86.27%. Alternately, fine ore was directly subjected to magnetic separation at 8000 Gauss, enriching the ore to 65.12%Fe with 48.15% yield which corresponds to 52.81% Fe. Thus, gravity concentration followed by magnetic separation gave higher grade, yield and Fe recovery.

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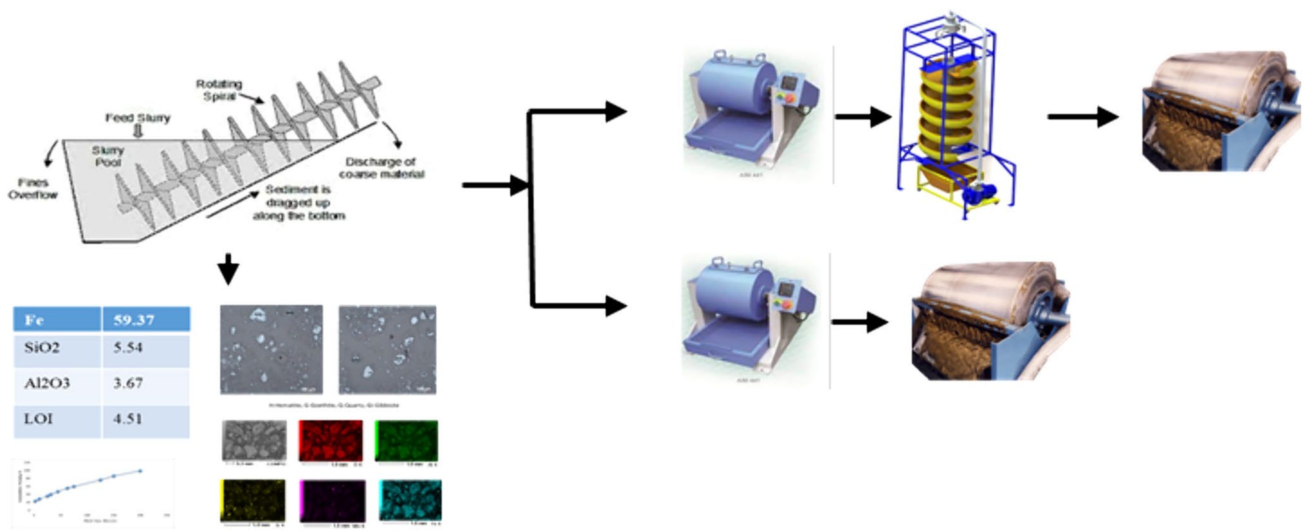
Graphical Abstract



Keywords Beneficiation · Spiral classifier oversize · Gravity separation · Magnetic separation

1 Introduction

In India, about 450 MTPA of high-grade iron ore in the form of calibrated ore, sinters, and pellets are required for the meeting the target of 300 MTPA by 2030-31 as per national steel policy. Utilizing the low and lean grade iron ore through the beneficiation process is vital to meet the production requirements [1, 2].

The amount and kind of gangue found in the ore body typically determine how iron ores are processed. The gravity and magnetic separation processes are the most frequently utilized beneficiation procedures for iron ores [3]. For iron production, iron ores with a Fe concentration of at least 65% are often preferred, to increase the productivity of iron making processes. Iron ores with low grade ore with a alumina/silica ratio greater than 1 are undesirable as there are problems in sintering the ores and smelting in blast furnace [4]. The high alumina ore forms viscous slag during smelting and requires a high coke rate [5]. Two units of silica reduction and 1 unit of alumina reduction in beneficiation plant will reduce 44 kg/t. Hot Metal (1–2) slag rate in Blast furnace. This phenomenon of forming viscous slag and high coke rate consumption during blast furnace operations is mainly due the presence of the silica and alumina in higher numbers in the ore [6]. This becomes an alarming appeal to researchers in the field of mineral processing to look into best beneficiation process in order to enrich the Fe content in the ore for best utilization in blast furnace operations.

The amount of iron ore fines added to blast furnace operations accounts for 30% along with 20% sinter and high grade ore. The productivity of hot metal increases by 2% for every 1% Fe increase in the concentrate. This leads to a 1.8% and 0.9% reduction in the needs for coke and limestone, respectively [7]. Thus, beneficiation comes the need of the hour in saving huge amounts by enriching the 1% Fe. From the literature, it is evident that gravity separation was improved by the beneficiation process in conjunction with desliming and high-intensity magnetic separation, and flotation techniques were able to upgrade the slimes with 59.22% Fe to concentrate 64.8% Fe with a 74% yield [2]. Additionally, it has been observed that the conventional beneficiation method may increase the Fe content to 66.97% from 37.86% Fe with a yield of 14.4% [8]. After desliming and grinding the slimes, high-intensity magnetic separation was performed; this increased the concentrate's Fe content to more than 64% Fe from 58.13% feed, yielding a yield of more than 60%[9].

The feed to the beneficiation plant contains iron ore with 55% Fe, and it was subjected to processing as shown in Fig. 1. The ore was subjected to crushing in ball mill followed by screening. The + 3 mm ore was circulated to crushing. The undersized fraction(− 3 mm + 150 mm) was subjected to spiral classification. The − 150 µm fraction was subjected to gravity concentration. The tailing from the gravity concentrator was further subjected to magnetic separation. The concentrate from Spiral Concentrator and the magnetic fraction of magnetic separator are treated

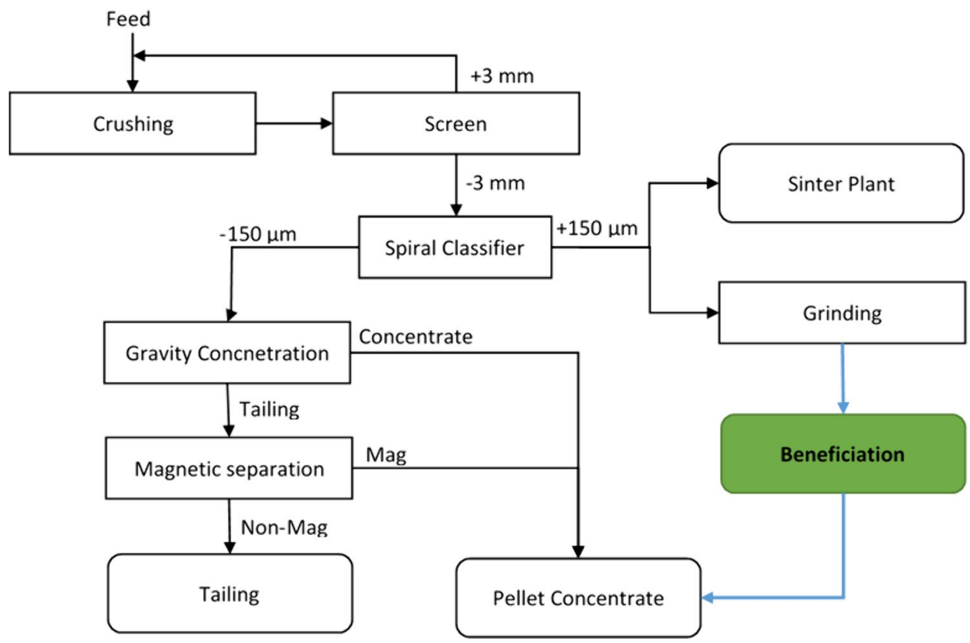


Fig. 1 Flowsheet of existing and proposed beneficiation route

together as a pellet concentrate. The present study deals with the + 150 µm fraction from the spiral classifier as input material for sinter being further enriched and beneficiated to find its suitability as a pellet feed. The ore fraction of the spiral classifier output of the + 150 µm slurry is the focus of the present study. This fraction which has been used for use as sinter feed has 59% Fe. This feed material slurry was subjected to two different beneficiation routes to enrich the Fe content and material yield. The fine particulates slurry post-grinding was subjected to (i) Spiral classification followed by magnetic separation and an alternate route involving only magnetic separation. Figure 1 gives the idea of existing and proposed beneficiation route.

2 Materials and Methods

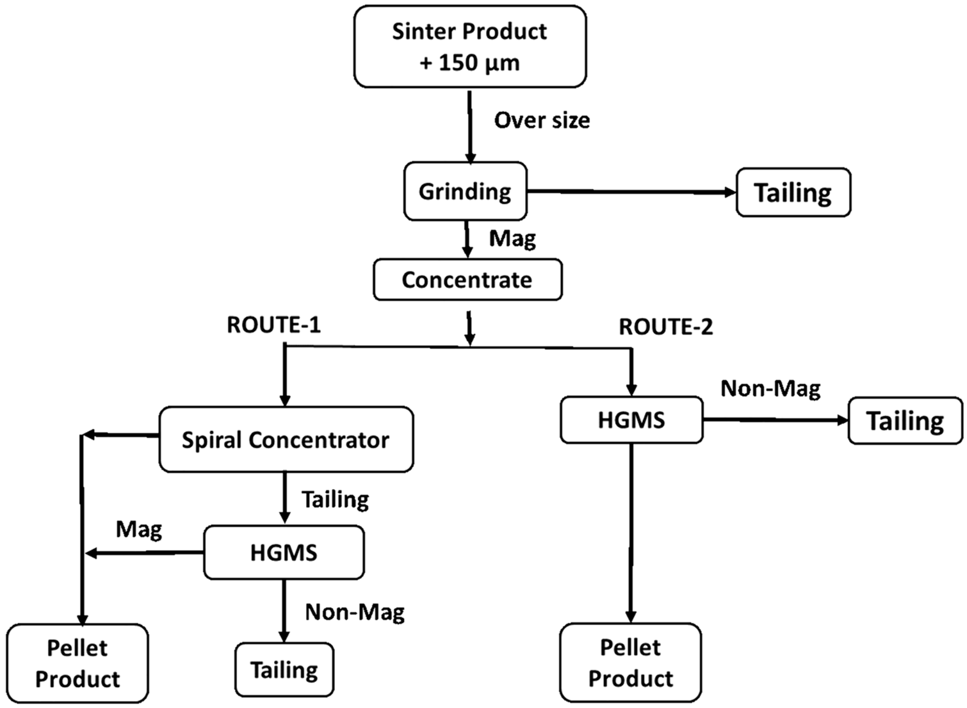
The sample used for beneficiation studies was obtained from ore beneficiation plant, JSW steel Ltd, Vijayanagar. Around 100 kg's of the representative sample (i.e., spiral classifier underflow + 150 microns) was collected and had been done sampling to get the representative sample. Around 1 kg of the as-received sample was taken to carry out the characterization studies such as XRF (X-ray fluorescence), XRD (X-ray Diffraction), EDS (Energy-Dispersive X-ray Spectroscopy) (1–2) elemental mapping and liberation studies.

3 Experimental Methods

The representative samples (classifier underflow + 150 microns) were obtained from beneficiation plant. The + 150 µm fraction which is considered as sinter feed (at JSW beneficiation plant) was subjected to grinding in a ball mill to a slurry. The slurry concentrator was subjected to two routes for processing as shown in Fig. 2. The slurry concentrator post-grinding was subjected to spiral concentrator supplied by Mineral Technology, where the concentrate was enriched with Fe 61.31%. The tailing was further subjected to magnetic separation in lab scale Metso make HGMS at different Gauss values. The concentrate from magnetic separation was also combined with the concentrate from the spiral. In an alternate route, the slurry from the grinder was subjected to magnetic separation in a Metso make High Gradient Magnetic separator (HGMS) at a magnetic field intensity between 6000 and 10,000 Gauss. The magnetic fraction is treated as a concentrate for pellet. The non-magnetic portion was sent as tailing. The Fe content and the yield of the concentrate and the extent of Fe recovery were estimated. Table 1 gives the conditions of the equipment.

Selected samples were subjected to characterization in terms of particle size analysis, chemical composition using Thermo-Fisher make Model: 9900WS X-Ray Fluorescence spectroscopy, JOELJXA-8230 make Electron Probe Microscopic Analyzer (EPMA). Samples were analyzed using Optical Microscope of model Axivert 40MAT, make-Carl Zeiss-Germany, resolution – 0.25 microns, Rhodos particle size analyzer. Figure 2 gives the proposed beneficiation route.

Fig. 2 Flowsheet of proposed beneficiation route



4 Results and Discussion

4.1 Characterization Studies of the Sinter Feed Sample (Spiral Classifier Underflow)

The chemical analysis of the input ore for sinter product is shown in Table 2. The sample contains 59.37% Fe, 5.54% SiO_2, 3.67% Al_2O_3 and 4.51% LOI. The particle size distribution of the sample in this study (Rodos particle analyzer) is shown in Fig. 3. The particle size analysis of the sample shows that the D80 of the sample is approximately 2.6 mm. Table 2 gives the chemical analysis of the spiral classifier oversize.

Table 1 : operating conditions of Equipment

Unit operation	Parameters
Spiral classifier	% of solids: 35%, Screw speed: 30 rpm
Spiral concentrate	Feed density—1.20 gm/cc, Flow rate: 43 rpm
HGMS	Feed density—1.35 g/cc, Field intensity – 6000, 8000 and 10,000 Gauss

Table 2 chemical analysis feed sample

Fe	SiO_2	Al_2O_3	LOI
59.37	5.54	3.67	4.51

4.1.1 X-Ray Diffraction Analysis (XRD) of Spiral Classifier Underflow

The X-ray diffraction analysis (XRD) of the sample is shown in Fig. 4. For the analysis it can be evident that iron oxide is available in the form of hematite and goethite. Hematite is the predominant iron oxide present. Silica and alumina are the major gangue minerals present in the ore. Silica is present in the form quartz and alumina is present in the gibbsite.

4.1.2 EDS Elemental Mapping Analysis

EDS analysis was carried out using JOELJXA-8230. From Fig. 5, the results show that the Fe_2O_3 is strongly associated with Al_2O_3 and SiO_2. The MnO association is very less.

4.1.3 Microscopic Studies

The representative sample was subjected for microscopic studies. From the studies, it is observed that hematite is the predominant mineral present in the sample with sub-ordinate amounts of Goethite and quartz and kaolinite are major gangue minerals. The bright color particles are hematite mineral, and red color particles seem to be goethite which is identified on

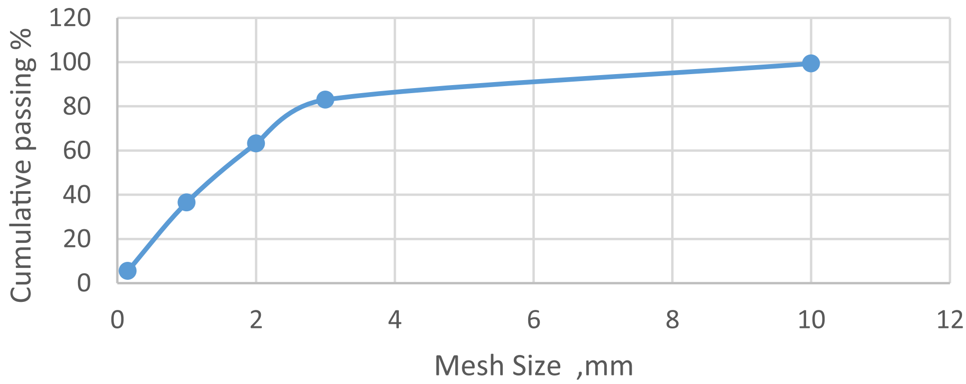


Fig. 3 Particle size distribution of feed sample(Spiral classifier overflow)

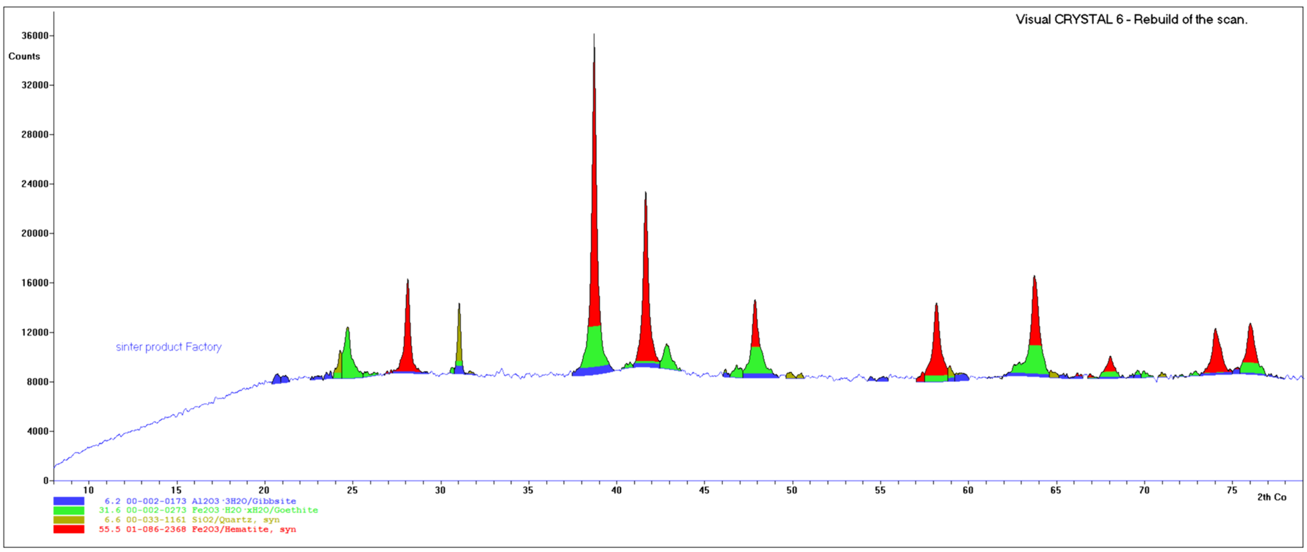


Fig. 4 XRD analysis of feed sample

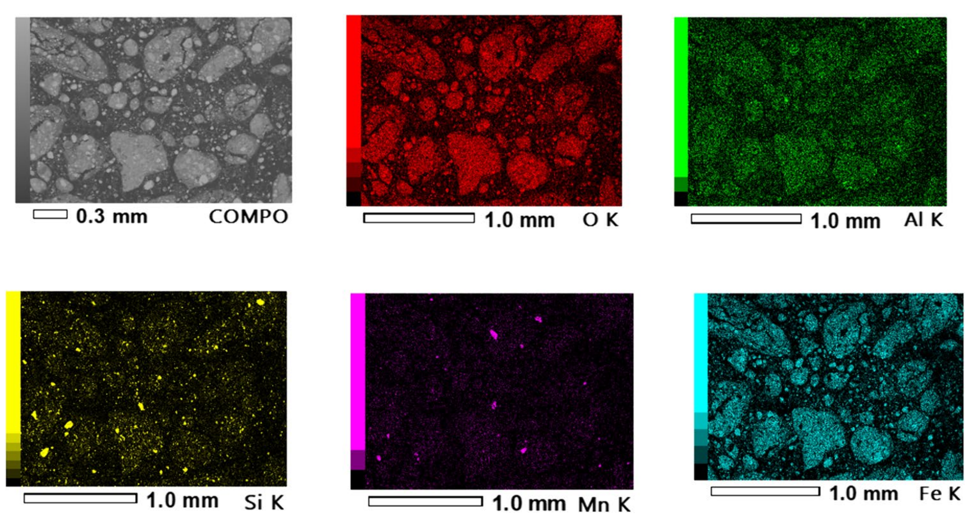


Fig. 5 EDS Elemental mapping analysis of feed sample. From the figure it can been seen that both Fe and Al_2O_3 are shaded in the same region along with oxygen

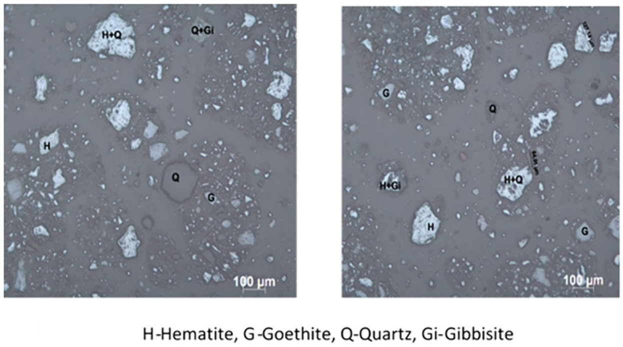


Fig. 6 Optical images of feed sample

the basis on the optical properties of the individual mineral. Black and dark brownish particles are kaolinite and quartz minerals, respectively. The micrographs show that mineral particles are in finely disseminated form. The sample still needs liberation for separation of gangue form Fe. Free Fe particle is found around 127 microns, whereas free silica is found around 80 microns. Figure 6 shows the optical images of classifier oversize material.

4.2 Comparison of Beneficiation Routes

The feed to the beneficiation plant is subjected to different unit operation in order to enrich the Fe value with best recovery and will provide the material to pellet and sinter making. At times, the requirement of the pellet overcedes the sinter. In such a case, the sinter product from the beneficiation plant has to be further beneficiated in order to make it viable for pellet making. So these studies focus on the enrichment of the Fe from sinter product to make it viable for pellet making.

As shown in Fig. 2, the sample is subjected to two beneficiation routes in which the former involves gravity separation followed by magnetic separation and the later involves separation only by magnetic separation. The detailed study of the two routes is given below.

4.3 Beneficiation Studies

To enrich the Fe content in the Spiral classifier oversize (sinter product), the sample was ground in a ball mill for size reduction. The material was ground in a single-stage ball mill (80% passing 130 µm approximately).

The sinter product after grinding had a slurry density 1.15 gm/cc and 40 mm splitter position was maintained. The slurry was subjected to two different beneficiation routes as shown in Fig. 2. In the first route, after spiral concentrator the concentrate composition is shown in Table 3 and the yield was 75.25% and the tailing was 24.75%. The 24.75% tailing fraction obtained was subjected to HGMS with varying magnetic fields, and the results are shown in Table 4. The optimum field could be obtained with 8000 Gauss. The spiral concentrate gave a concentrate with 61.31% Fe with 75.25% Yield and 77.71% Fe recovered. The concentrate from the 24.75% tailing generated from the spiral concentrator was treated with HGMS. The optimum result was observed at 8000 Gauss with ~ 62% Fe and ~ 33% Yield. The overall pellet concentrate achieved was 61.38% Fe, 4.53% SiO_2, 2.97% Al_2O_3 and 83.45% Yield (Fig. 7).

Prasad et al. demonstrated that a concentrate with an overall iron recovery of 56% could be achieved by assaying 63% Fe and 3.3% alumina from 55% Fe, with the use of a wet high-intensity magnetic separator and a hydrocyclone for categorization [10] (Table 5).

In the second route the spiral classifier oversize after grinding was fed to Metso High Gradient Magnetic Separation (1–2) at varying field intensity of 6000, 8000 and 10,000 Gauss as shown in Table 6. The concentrate at

Table 3 Results of spiral concentrator(Route-1)

Product	Wt%	Wt% w.r.f	Fe	SiO_2	Al_2O_3	LOI	Fe recovery
Feed	100	100	59.37	5.54	3.67	4.51	**77.71**
Concentrate	**75.25**	**75.25**	**61.31**	**4.63**	**2.99**	**3.49**	
Tailing	24.75	24.75	53.47	8.31	5.74	7.62	

Table 4 Results of magnetic separation (Route 1)

Magnetic field intensity (Gauss)	Product	Wt%	Wt% w.r.f	Fe	SiO_2	Al_2O_3	LOI	Fe recovery
6000	Mag	22.09	5.47	62.90	3.38	2.57	3.19	5.79
	Non-Mag	77.91	19.28	50.76	9.70	6.62	9.08	
8000	**Mag**	**33.12**	**8.20**	**61.98**	**3.61**	**2.80**	**3.79**	**8.56**
	Non-Mag	66.88	16.55	49.25	10.60	7.22	9.76	
10,000	Mag	36.39	9.01	61.22	3.86	3.07	4.28	9.29
	Non-Mag	63.61	15.74	49.08	10.89	7.26	9.00	

Fig. 7 Particle size distribution of the grinded sample

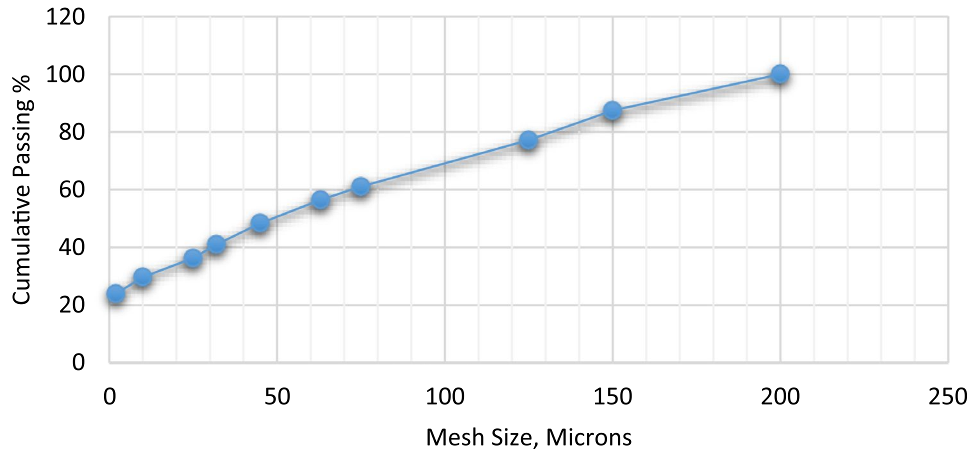


Table 5 Results of final concentrate and tailing (Route-1)

Product	Wt% w.r.f	Fe	SiO_2	Al_2O_3	LOI	Fe recovery
Feed	100	59.37	5.54	3.67	4.51	
Total concentrate	83.45	61.38	4.53	2.97	3.52	86.27

Table 6 Magnetic separation results (Route-2)

Magnetic field intensity (Gauss)	Product	Wt%	Fe	SiO_2	Al_2O_3	LOI	Fe recovery
	Feed	100	59.37	5.54	3.67	4.51	
6000	Mag	40.49	63.83	3.41	2.17	2.79	43.53
	Non-Mag	59.51	56.25	6.95	4.68	6.31	
8000	**Mag**	**48.15**	**65.12**	**2.28**	**2.12**	**2.30**	**52.81**
	Non-Mag	51.85	54.04	8.67	5.24	6.41	
10,000	Mag	51.48	64.13	3.29	2.08	2.40	55.60
	Non-Mag	48.52	54.29	7.87	5.23	6.37	

Table 7 Final accumulated results of Route 1&2

Description	Wt%	Fe,%	SiO_2,%	Al_2O_3,%	LOI,%
Feed	100.0	59.37	5.54	3.67	4.51
Route -1 (Gravity concentration followed by magnetic separation)					
Spiral Concentrate(Conc#1)	75.25	61.31	4.63	2.99	3.49
Spiral Tailing	24.75	53.47	8.31	5.74	7.62
HGMS Mag (8000 Gauss)- (Conc#2)	8.20	61.98	3.61	2.80	3.79
HGMS N Mag (Tailing #1)	16.55	16.55	49.25	10.60	7.22
Final Concentrate	83.45	61.38	4.53	2.97	3.52
Final Tailing	16.55	49.25	10.60	7.22	9.76
Fe Recovery,%	86.27				
Route -2 (only magnetic separation)					
HGMS Mag (8000 Gauss)- (Conc#1)	33.12	61.98	3.61	2.80	3.79
HGMS N Mag (Tailing #1)	66.88	16.55	49.25	10.60	7.22
Final concentrate	42.57	59.49	9.91	2.86	2.99
Final tailing	49.13	37.20	36.16	4.48	4.68
Fe recovery,%	**52.81**				

8000 Gauss, Fe enriched to 65.12% Fe with 48.15 Yield and 52.81% Fe recovery. Further, increasing magnetic field results in a slight improvement in yield and reduction of concentrate grade. This is due to the phenomena of entrainment of *gangue*. Das et al. [11] used hydrocyclone classification and high intensity magnetic separation to study the washing of iron ore slimes. Their findings suggested that it is possible to obtain a concentrate assaying 60–65% Fe with 60–80% recovery [11]. Table 6 gives magnetic separation results of the spiral classifier oversize material.

5 Conclusion

Beneficiation involving gravity separation followed by magnetic separation gave good results. That is 83.45 percent of the yield is recovered with 61.38 grade Fe where as the route −2 in which only magnetic separation is involved gave 42.57% concentrate weight recovery with 61.89% Fe grade. The gravity separation followed by magnetic separation gave good yield because most of the valuable minerals in the feed are recovered as there is substantial gravity difference between the valuable and gangue minerals (i.e., Fe, quartz and alumina) and which every valuable particles left over in the tailings are recovered by processing them HGMS by using the property of magnetic separation. Where as in route 2 in which only magnetic separation is employed here, the yield is very less because only magnetic property is employed in gangue finer size particles flow along with valuable minerals which is due to entrainment. Table 7 gives the accumulated results of proposed two routes.

- The as-received sample (i.e., sinter product) contains about 59.37% Fe, 5.54% SiO_2, 3.67% of Al_2O_3 and 4.51% LOI.
- The D80 of the as-received sample is approximately 2.6 mm.
- From the XRD analysis, it is evident that hematite and goethite are the major iron-bearing minerals, whereas silica and alumina are the major gangue which are present in the form of quartz and gibbsite.
- From EPMA analysis, it is observed that silica is present along with Fe as pockets and it still needs to be grinded for further liberation complete liberation of Fe and silica.
- Optical microscopic studies state that free iron particle is liberated at approximately 127.6 microns size and free silica particle is available at approximately 80 microns. So the particle needs to be grounded below 150 microns for better liberation of the gangue for iron-rich mineral.
- And it is also observed that gangue is available in the form of pockets along with Fe.
- The spiral classifier followed by the magnetic separation process (scheme-1) is more efficient for iron recovery and grade improvement.
- The scheme-1 flow sheet achieved the concentrate with 61.38% Fe and 83.45% yield.
- The scheme-2 flow sheet achieved the concentrate with 65.12% Fe and 48.15% yield.

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Author Contributions Vijaya Mitra Duggirala contributed to Conceptualization, Methodology, Experimentation, and Writing—Original draft preparation. Kevin Jason contributed to Experimentation, Data curation, and Visualization. Karthik Paramasivan contributed to Supervision and Writing—Reviewing and Editing. Uma Devi contributed to Supervision and Writing—Reviewing and Editing. Rameshwar Sah contributed to Supervision.

Declarations

Conflict of interest The authors declare no conflict of interest.

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