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Studies on Beneficiation of Manganese Ore through High Intensity Magnetic Separator

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Abstract: Upgradation techniques like wet sieving and magnetic separation were used to evaluate the beneficiation potential of manganese ore. During wet sieving, manganese content in raw ore was upgraded from 27% to a maximum value of 38% in the concentrate with a recovery of 30%. Size classification was found to have no measurable effect on manganese grade in magnetic separation. In the unsieved ground ore, manganese content of 45% was achieved with a recovery of 23% and Mn/Fe ratio of 19% at a magnetic intensity of 8500 Gauss. At the same operating conditions, SiO_2 was reduced from 56% in the raw ore to 30% in the magnetic fraction. So, wet sieving technique leads to a comparatively lower manganese grade but better recovery. Conversely, a magnetic separation technique produced higher manganese grade but relatively lower recovery. Blending of the upgraded manganese ore with high grade iron ore can be done to achieve the required Mn/Fe ratio.
Keywords: Upgradation; Size classification; Magnetic intensity; Blending.

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1. Introduction

Almost 90-95% of manganese in the form of its alloys is consumed in steel production. It is a powerful reducing, desulfurizing and dephosphorizing agent imparting malleability, tenacity, and hardness to steel. Rest of the manganese is used in the production of dry cell batteries and as dietary additives [1, 2]. Generally, the production of manganese alloys requires ores with manganese content greater than 30% and manganese/iron ratio greater than 5 [1]. Ores with a low manganese content (~12% or less) [3,4] can be utilized in the production of manganese pig iron [5, 6]. The global production of raw and up-graded manganese ore is assessed to be around 17 million tonnes [5,7].

Beneficiation of low and medium grades manganese ores can be performed using chemical or physical techniques. Magnetic separation is one of the means of physical upgradation of manganese ore. Magnetic separators facilitate the separation of magnetic and non-magnetic fractions based on the difference between magnetic properties of target mineral and gangue materials. This technique has the advantages of large capacity, low operating cost, and lower environmental pollution [8]. All minerals are affected in some way, when subjected to a magnetic field and may behave either as magnetic, diamagnetic, or paramagnetic based on their magnetic properties [9].

In mineral processing, magnetic separation can be carried out either at low intensity, high intensity or high gradient. The Low-Intensity Magnetic Separators (LIMS) are suitable for minerals having strong magnetic susceptibility while High-Intensity Magnetic Separators (HIMS) is a preferred choice for minerals with weak magnetic susceptibility. The applied magnetic field for LIMS and HIMS is ∼1,000 gauss and ~2,000 gauss, respectively. The High Gradient Magnetic Separators (HGMS) are generally employed for the recovery of excellent size weakly magnetic minerals [10, 11]. Similarly, the magnetic separation can be conducted in both wet and dry modes. Dry magnetic separators have excellent performance for separation of minerals having a particle size higher than 75 μm, while wet magnetic separators give best separation results for feed containing large portions of fines [12].

Upgradation of manganese and iron ores through magnetic separation has been studied from different aspects by various researchers. Wang et al. [13] found that the friction between the grinder walls and the mineral particles caused the agglomerated mineral particles to disperse, thereby improving the efficiency of the magnetic separation process. Chen et al. [10] achieved a high-grade concentrate at a high magnetic induction due to the rotation of matrix in the magnetic field. According to Tripathy and Suresh [14], the significant parameters manipulating the efficiency of a High Intensity Induced Roll Magnetic Separator (IRMS) are feed rate, splitter position, roll diameter, roll speed, pole shape, pole gap, applied current, feed characteristics like size and susceptibility of mineral particles, shape, density, and electrostatic charging of particles. Ge et al. [15] reviewed the magnetic matrices used in HGMS. The magnetic field gradients in matrix separators were found to be much higher than that of separator without matrix. Liu et al. [16] performed the roasting of ferruginous manganese ore under reducing environment roasting followed by magnetic separation. It was found that although the high temperature was beneficial for the recovery of iron, however, it negatively affected manganese recovery at temperatures greater 800 ^oC. Subrat et. al [17] attempted the magnetic upgradation of manganese ore containing high silica. The feed ore with 22% Mn was upgraded to more than 42% Mn with a recovery of 59%. In another study on low-grade siliceous manganese ore, Mishra et. al. [18] performed dry and wet magnetic separation of the feed ore. Dry magnetic separation gave better results in terms of grade and recovery, where the raw ore was upgraded from 26% Mn to >46% Mn with a recovery of > 69% as compared to the wet separation technique, where the grade and recovery were >42% Mn and >56%, respectively at a magnetic intensity of 10000 Gauss. Peng et. al. [19] found that the optimum magnetic intensity for separation of iron from iron-bearing manganese residues was 1000-1200 Gauss and that for manganese was 11000-12000 Gauss. Iron and manganese were upgraded from the initial concentration of 16.79% and 15.12%, respectively to 62.21% and 35.21%, respectively.

The major manganese deposits in Pakistan, which constitute almost 97% of the total reserves, are located in the Khyber Pakhtunkhwa Province, Baluchistan Province, and the Federally Administered Tribal Areas (FATA) [4, 20-22]. **Figure 1** shows the detailed geological map of Nasir Area of Prang Ghar, located in Mohmand Agency.

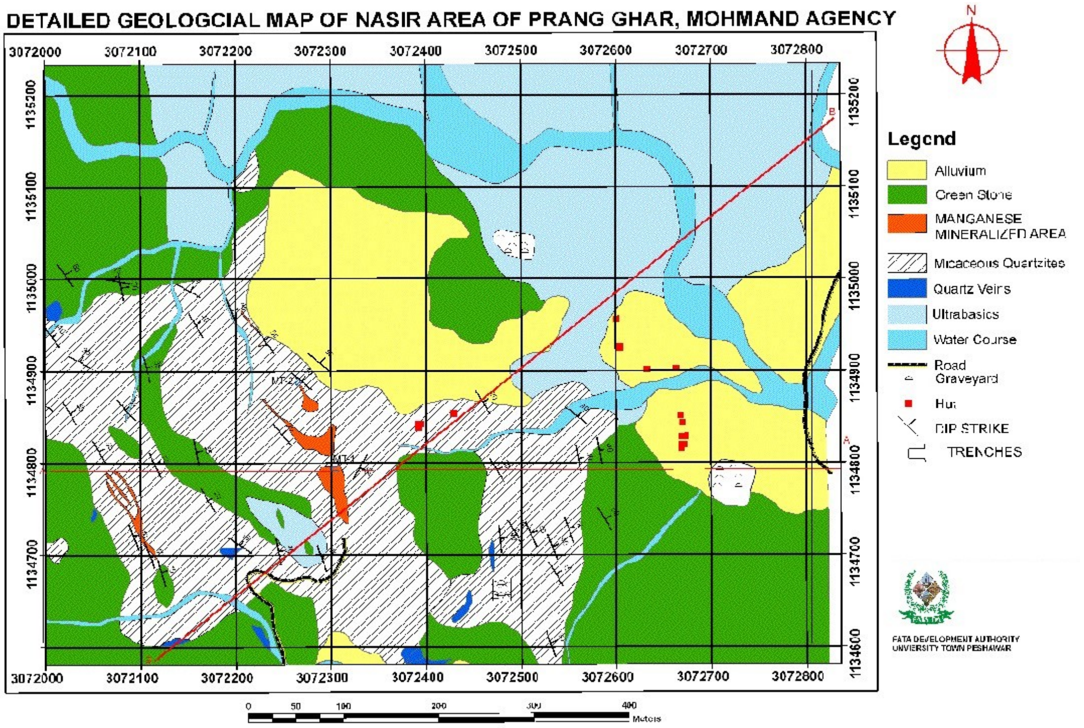

Figure 1. Detailed geological map of Nasir Area of Prang Ghar, Mohmand Agency

To the best of our knowledge, no systematic study has been adopted for the upgradation of the indigenous manganese ore of Mohmand Agency, Pakistan for subsequent utilization in the ferromanganese industry. To fill this gap, we attempted to beneficiate the manganese ore of Nasir Area of Prang Ghar, Mohmand Agency. The ore was subjected to size classification through wet sieving and magnetic upgradation techniques, and then the concentrate was evaluated for manganese grade and recovery. The study will set a baseline for linkage between exploration of indigenous manganese ore deposits, the beneficiation of these ores through simple and efficient techniques, and the consumption of the beneficiated ore into iron, ferromanganese, and steel industry.

2. Materials and methods

The bulk samples of manganese ore were crushed in a blake type jaw crusher. The crushed samples were then fine ground in a rod mill and subsequently wet-sieved in the size fractions of 1650, 150, 75, and 45μm, respectively.

The dried sieve fractions obtained from wet sieving were analyzed by XRF, model S4 Pioneer, Bruker, Germany to determine chemical composition.

High-intensity magnetic separator, model Makwell XL-21, China was used to conduct magnetic beneficiation studies at intensities of 2500, 5000 and 8500 Gauss, respectively. The concentrate and tail fractions were analysed for chemical composition by previously described XRF.

The ground manganese ore was analysed on X-Ray Diffractometer (Rigaku, Japan) with copper tube. Start angle was 2° while stop angle was 65° with a step time of 1 second and wavelength of 1.5405 °A.

Scanning Electron Microscope (JSM6380, JEOL, Japan**)** accompanied with Energy Dispersive X-Ray Analyser was used to analyze the manganese ore samples. The instrument was operated at 20.0 kV and probe current of 1.0 nA with counting rate of 197-242 counts per second.

3. Results and discussion

3.1 Petrographic study

Almost all the groundmass is composed of manganese ore. Quartz grains occur in clusters and are fractured and manganese ore is penetrated along the fractures and all around quartz. Quartz grains are larger and generally range from 0.15 to 0.40 mm in size. Ore contain mineral phases like braunite ($Mn^{2+}Mn^{3+}_6(SiO_4)O_8$), pyrolusite ($MnO_2$), and bixbyite ($(Mn, Fe)_2O_3$). White grains of pyrolusite occur in large amounts and are of larger size i-e about 0.60 mm to 1.00 mm. Brownish yellow braunite grains form mesh spread throughout the pyrolusite grains while bixbyite occurs in granular form. Both the braunite and bixbyite occurs as inclusions in the pyrolusite.

3.2 XRD analysis

Figure 2 shows the XRD analysis of manganese ore. Braunite and quartz are the major mineral phases distributed in the ore. Braunite is a silicate mineral which forms grey/black tetragonal crystals containing both di- and tri-valent manganese. Braunite occurs at d-values of 2.724 and 2.363 in the XRD pattern. SiO_2 in the form of quartz is distributed in the ore at d-values of 4.277, 3.361, 2.466 and 2.288. Moreover, braunite and quartz collectively appear at d-values of 2.149, 1.822, 1.664 and 1.544.

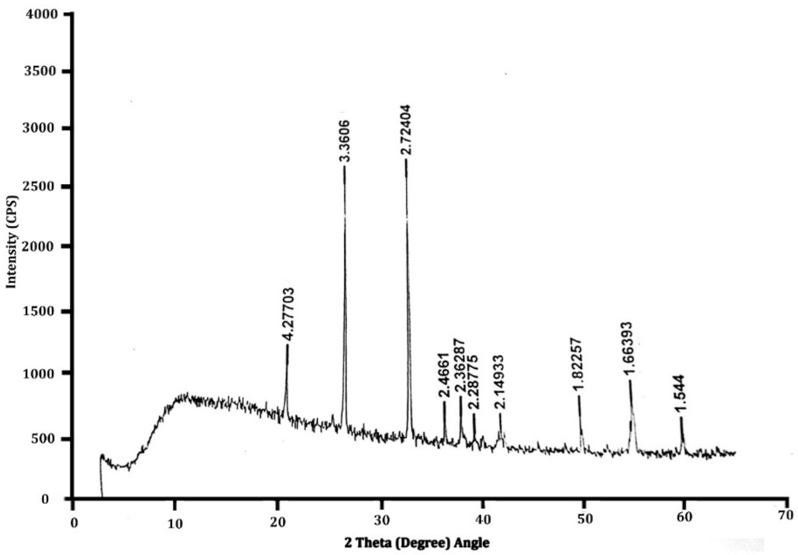

Figure 2. XRD analysis of raw manganese ore

3.3 SEM-EDX analyses

Manganese ore was subjected to SEM and EDX analysis shown as **Figure 3**. As discussed in the petrographic study, different mineral phases of manganese occur in a very close association with each other in the form of interlocking grains, so the SEM study could not provide the analysis of any one of the pure minerals. However, it confirms the presence of predominant phases of braunite, pyrolusite, and bixbyite as were found in the petrographic study. The presence of carbon in SEM analysis shows the presence of some carbonate phase too. As there could not be identified any other carbonate mineral in the thin section study so that this carbon may be attributed to the presence of a carbonate mineral of manganese, most probably rhodochrosite. This mineral could not be identified in petrographic and XRD studies because of the collective occurring of many manganese mineral phases.

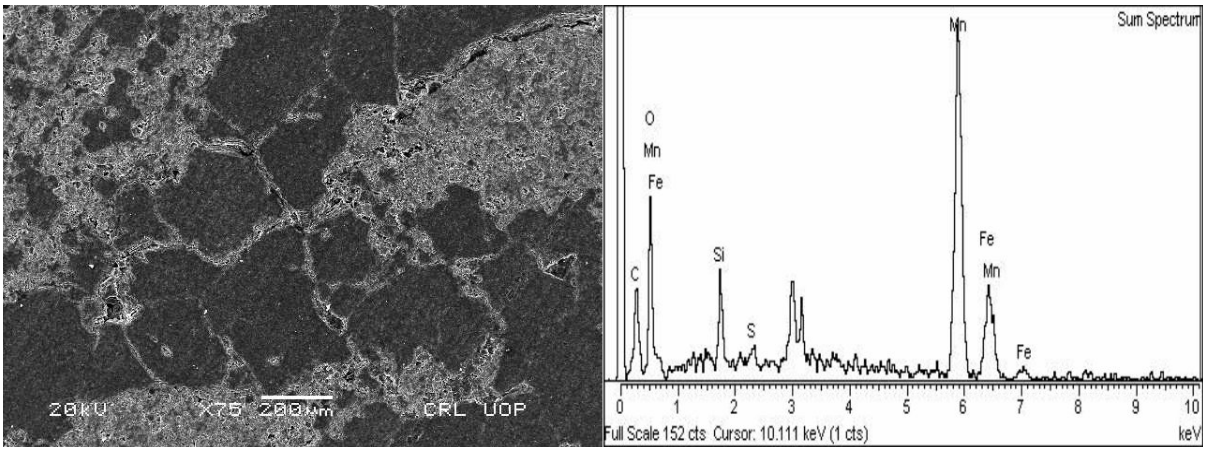

Figure 3. SEM and EDX of raw manganese ore

The results of all of the mineralogical studies (petrography, XRD, and SEM-EDX) support each other, and thus there is a conformity in the results. These results indicate the presence of manganese in two different mineralogical forms; the manganese oxides and manganese silicates. Braunite is the silicate phase mineral, and it is the major mineral phase occurring in the ore. Pyrolusite and bixbyite are the oxide minerals which occur as minor phases. The low manganese (~27%) and high silica (~56%) content in raw manganese ore makes it unsuitable for direct consumption in the production of ferromanganese. However, upgradation of the ore can increase its commercial value

3.4 Wet sieving

In raw ore, the liberation of the target minerals from the gangue materials can be accomplished by size reduction. During the grinding process, the narrowly interconnected minerals are separated from the gangue material, and thus upgradation is facilitated. If weak boundaries exist between the target and gangue minerals, then preferential breakage may occur and separation between minerals takes place at grain size of the individual minerals. The ore is ground until target minerals and gangue material are liberated from each other. Wet sieving was conducted at size fractions of -1650μm+150μm, -150μm+75μm and -75μm+45μm, respectively. **Table 1** shows the distribution of various minerals in each size fraction. **Figure 4** shows that wet sieving enhanced the manganese content to 38% with a recovery of 30%, and reduced silica to 40% with manganese/iron ratio of 24 in the size range of -75μm+45μm. It can be further observed that the manganese content increases while its recovery decreases as the particle size fraction decreases. The enhancement of manganese content and decrease in silica content shows that the minerals were liberated from each other and confirms the finer grain size of manganese and coarser grain size of silica.

Table 1. Distribution of Minerals in Raw Ore and Various Size Fractions of Manganese Ore

Particle Size μm	MnO %	Fe_2O_3 %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	P_2O_5 %
Raw ore	35.360	1.457	56.310	2.130	1.955	1.323	0.089
-1650+150	28.330	1.222	65.170	1.990	1.391	1.050	0.071
-150+75	40.690	1.500	51.120	2.720	1.840	1.350	0.100
-75+45	49.510	2.303	40.190	2.330	2.879	1.815	0.150

3.5 Magnetic separation

Magnetic separation study was conducted at magnetic intensities of 2500, 5000, and 8500 Gauss for each of the size fraction of -1650μm+150μm, -150μm+75μm and -75μm+45μm, respectively. **Table 2** and **Figures 5-9** show the analysis of a magnetic fraction of the upgraded ore. It can be observed that the lower magnetic intensity leads to lower manganese recoveries in various size fractions. The manganese content remained almost the same in different size fractions at magnetic intensities of 5000 and 8500 Gauss. However, manganese recovery was enhanced at 8500 Gauss. It can be further seen that at an intensity of 8500 Gauss, the manganese content decreased and its recovery increased as the particle size fraction decreased. The optimum manganese content of 45.20% (**Figure 5**) was achieved with a recovery of 23.35% (**Figure 6**) in the unsieved ground ore at a magnetic intensity of 8500 Gauss. At the same operating conditions, Fe content was 2.37% (**Figure 7**) and its recovery was 32.90% (**Figure 8**), while Mn/Fe ratio was 19.00% (**Figure 9**) and SiO_2 reduced to 30.40% (**Table 2**). As discussed earlier, dry magnetic separators yield best separation results for materials coarser than 75 μm [11]. Using unsieved ground ore makes the process more economical as it saves the cost for size classification. The lower manganese recovery can be attributed to the tight trapping of non-magnetic particles having a fine size, in the inner layer of the bunch of magnetic particles, which certainly limits the manganese grade and recovery in the process [6]. It is also important to note that the increase in magnetic field intensity does not necessarily cause an improved separation of magnetic and non-magnetic fractions. Very high magnetic intensity may lead to an increase in the capture of weakly magnetic gangue particles, which thus reduce the recovery of valuable mineral [7]. The lower recovery of manganese may also be attributed to the scattering of fine size manganese particles within quartz and secondary silicification which prevents the complete release of the manganese oxide phase, even after fine grinding.

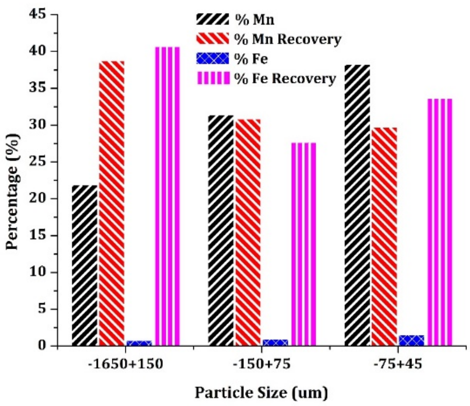

Figure 4. Manganese and Iron recoveries in various size fractions during wet sieving

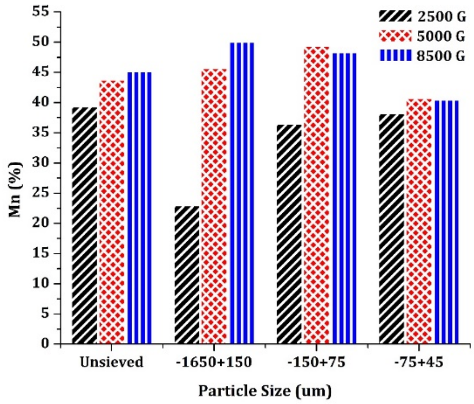

Figure 5. Manganese percentage in various size fractions at different magnetic intensities

Table 2. Distribution of Minerals in Concentrates of Magnetic Separation at Various Size Fractions

Particle Size µm	MnO %	Fe_2O_3 %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	P_2O_5 %
2500 Gauss							
Unsieved	50.850	2.530	37.510	2.210	3.540	2.530	-
-1650+150	29.710	11.310	48.570	2.390	3.970	2.850	-
-150+75	47.130	9.670	37.140	2.060	1.990	1.340	-
-75+45	49.340	4.185	38.380	2.360	2.746	1.711	0.115
5000 Gauss							
Unsieved	56.580	3.235	32.460	2.190	2.073	1.711	0.086
-1650+150	59.030	8.500	25.680	2.500	1.920	1.370	-
-150+75	63.750	3.242	26.290	2.890	1.835	1.100	0.068
-75+45	52.590	4.761	35.310	2.410	2.866	1.270	0.105
8500 Gauss							
Unsieved	58.360	3.387	30.360	2.450	2.123	1.703	0.093
-1650+150	64.620	4.079	24.910	2.830	1.669	0.866	0.055
-150+75	62.410	3.266	27.480	2.810	1.852	1.290	0.065
-75+45	52.310	3.598	36.260	2.200	2.873	1.592	0.124

4. Conclusion

The upgradation potential of the manganese ore Nasir area of Prang Ghar, located in Mohmand Agency, containing ~27% manganese and ~56% silica, was tested through wet size classification and magnetic separation methods. Wet size classification was conducted in the size range of -1650µm+150µm, -150µm+75µm and -75µm+45µm. Manganese content was beneficiated to a maximum of ~38% with a recovery of ~30% in the size range of -75µm+45µm. Magnetic separation was carried out at intensities of 2500, 5000 and 8500 Gauss and maximum manganese upgradation of ~45% was attained with a recovery of ~23% in the ground raw ore at the intensity of 8500 Gauss. At the same operating conditions, Fe content was 2.37%, and its recovery was 32.90%, while manganese/iron ratio was 19.00% and SiO_2 reduced to 30.40%. So, the manganese ore of Mohmand Agency can be physically beneficiated through both wet sieving and magnetic separation. Wet sieving will yield a comparatively lower manganese grade but better recovery. Conversely, magnetic separation will yield higher manganese grade but comparatively lower recovery.

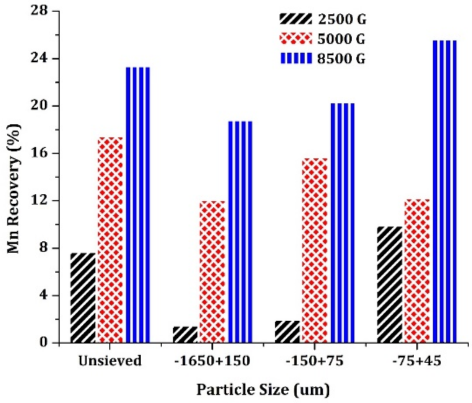

Figure 6. Manganese recovery in various size fractions at different magnetic intensities

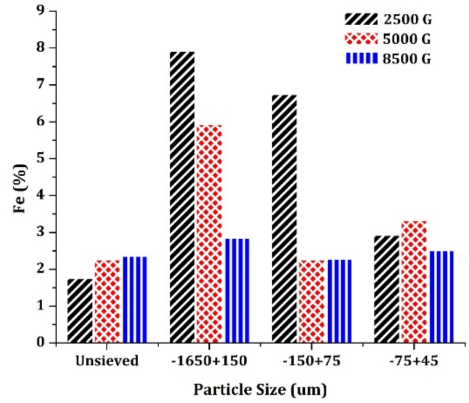

Figure 7. Iron percentage in various size fractions at different magnetic intensities

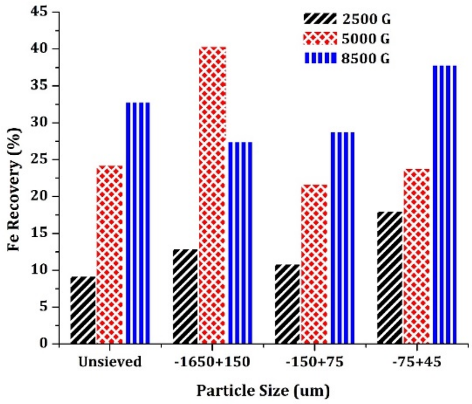

Figure 8. Iron recovery in various size fractions at different magnetic intensities

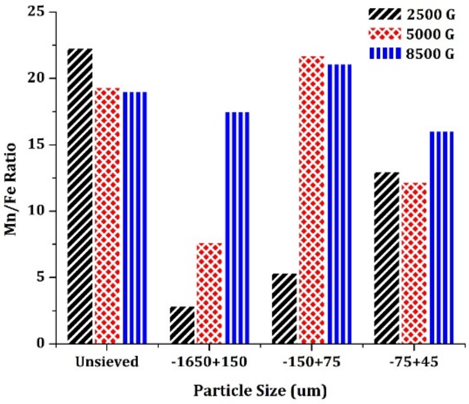

Figure 9. Manganese/Iron ratio in various size fractions at different magnetic intensities

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