Chaib, Abdeslam; Bouabdallah, Soufiane; Ferfar, Meriem et al.

Article

Investigation of physicochemical characterization and magnetic enrichment of iron ore from Sidi Maarouf deposit

Technology audit and production reserves

Reference: Chaib, Abdeslam/Bouabdallah, Soufiane et. al. (2024). Investigation of physicochemical characterization and magnetic enrichment of iron ore from Sidi Maarouf deposit. In: Technology audit and production reserves 1 (3/75), S. 9 - 14.
https://journals.uran.ua/tarp/article/download/297846/291160/688651.
doi:10.15587/2706-5448.2024.297846.

UDC 504.3.054
DOI: 10.15587/2706-5448.2024.297846

Abdeslam Chaib,
Soufiane Bouabdallah,
Meriem Ferfar,
Aissa Benselhoub,
Nadiia Dovbash,
Stefano Bellucci

INVESTIGATION OF PHYSICOCHEMICAL CHARACTERIZATION AND MAGNETIC ENRICHMENT OF IRON ORE FROM SIDI MAAROUF DEPOSIT

The establishment of a new metallurgical complex in Bellara, located in El-Milia in the Jijel region, is geographically advantageous due to its proximity to the Sidi Maarouf deposit (Algeria). This proximity has been a fundamental motivation for the completion of the current study. The object of research is the quality of iron products from Sidi Maarouf. The research is aimed at developing a treatment process aimed at improving the quality of iron products from Sidi Maarouf, while reducing the impurities of quartz and clay present in this ore. This approach will be based on an approved technological treatment scheme, implemented through an experimental approach to ensure reliable results that meet the requirements of the steel industry. The problem issue revolves around the difficulties encountered in the production of steels due to the natural characteristics of the raw material.

In the absence of a physico-chemical characterization of the Sidi Maarouf iron ore deposit, samples taken undergo a series of thorough analyses, including microscopic examinations, X-ray diffraction (XRD), as well as additional chemical analyses using X-ray fluorescence (XRF). The identified minerals are predominantly composed of hematite in terms of iron. As for the gangue, it is mainly composed of calcite and quartz. Through to the pre-treatment process involving washing, we have successfully removed lightweight particles, resulting in a concentrate containing dense particles. This approach was crucial in achieving satisfactory results during the high-intensity dry magnetic separation. As a result of the research it is shown that the enrichment of the Sidi Maarouf iron ore through high-intensity dry magnetic separation, a final concentrate was obtained with a Fe_2O_3 content exceeding 67 %, along with a significant reduction in silica impurities to 0.92 % and alumina to 0.77 %. It was concluded that this concentrate, derived from the −1+0.5 mm fraction and obtained under a current intensity of 12 A, meets the requirements of the steel industry.

Following the work carried out, it is found that the methods of valorization of iron ore through mineralogical processes consistently require a high level of efficiency and performance in terms of equipment and characterization of the products obtained. In the future, iron ore processing will be conducted using innovative methods, integrating advanced technologies to enhance its characteristics while adopting environmentally friendly practices.

Keywords: *iron oxide, characterization, steel industry, magnetic separation, washing, Jijel region, eastern Algeria.*

Received date: 26.12.2023
Accepted date: 01.02.2024
Published date: 08.02.2024

How to cite
Chaib, A., Bouabdallah, S., Ferfar, M., Benselhoub, A., Dovbash, N., Bellucci, S. (2024). Investigation of physicochemical characterization and magnetic enrichment of iron ore from Sidi Maarouf deposit. Technology Audit and Production Reserves, 1 (3 (75)), 9–14. doi: https://doi.org/10.15587/2706-5448.2024.297846

1. Introduction

The strong demand for steel in domestic and international markets has led to an increase in iron ore production to meet the needs of production and quality. Algeria has recently experienced significant economic development, especially in the mining sector, which has garnered renewed interest and new growth ambitions after a prolonged period of stagnation. Starting from 2020, the annual production volume of iron ore in Algeria will reach around two million tons; however, this quantity remains insufficient to meet the country's growing needs [1].

Iron stands out as an element abundantly present in the Earth's crust. Among the ferrous minerals of predominant industrial importance, oxides and hydroxides are primarily identified, with carbonates being of lesser significance. Iron itself is generally found in the form of magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite ($FeO(OH)$), limonite ($FeO(OH)\cdot nH_2O$), and siderite ($FeCO_3$) [2]. Iron ore is the raw material for primary smelting, which, in turn, is the main raw material for steel.

The importance attributed to iron content proves crucial in the context of the steel production process, as iron represents the fundamental element sought after. The fusible elements of the gangue, such as silica (SiO_2), lime (CaO), alumina (Al_2O_3), and magnesia (MgO), play a significant role in the formation of slag during the blast furnace process. Slag is a vitreous substance formed when these elements

ISSN 2664-9969

react with other components of the ore and additives. Their total mass and respective proportions influence the quantity and nature of additions needed to form the melting bed, which is essential for the smooth progress of the iron ore smelting process in the blast furnace. This consideration is essential throughout the metallurgical process, influencing decisions regarding ore enrichment and other key stages of treatment, aiming to achieve an optimal quality final product.

High-quality iron ores, intended for direct shipment, can generally be processed relatively simply. On the other hand, low-quality iron ores require additional beneficiation. Ore beneficiation encompasses all methods used to enhance the physicochemical characteristics and ensure an iron ore that meets the requirements of the steel industry.

The current treatment of iron ore relies on the application of new methods such as leaching and bioleaching, which have proven their effectiveness [3]. However, despite their undeniable economic importance, environmental protection imposes constraints on their widespread use. In this context, several researchers have explored the possibility of recovering iron from low-grade iron ores using techniques such as flotation, reverse anionic flotation of quartz, and magnetic separation [4, 5], gravity separation [6], froth flotation [7, 8], or a combination of these methods [9–11]. This physical approach helps limit chemical interactions and justifies itself as an attractive alternative to newer treatment techniques.

Until now, the valorization potential of the Sidi Maarouf deposit has largely remained unexplored, underscoring the significance of the research presented in this article.

The issue at hand revolves around the challenges faced in the steel industry due to the natural characteristics of the raw material (mineralogical composition, granulochemical composition). To meet the requirements of the steel industry, the presented study adopts an innovative approach aimed not only at enhancing the quality of the iron ore extracted from the Sidi Maarouf deposit but also at significantly reducing the impurity content through the application of new valorization methods.

This work aims to study iron ore valorization techniques, encompassing methods aimed at improving physicochemical characteristics. The ultimate goal is to ensure the production of iron ore that meets the technical requirements necessary for the production of different types of steel. This approach makes it indispensable for all relevant industries.

2. Materials and Methods

2.1. Geographical and geological setting of the Sidi Maarouf iron deposit. The Sidi Maarouf deposit is located in the North-East of Algeria, more precisely in the Little Kabylie, 85 km North-West of Constantine, 15 km South of El-Milia and 75 km South-East of Jijel (Fig. 1). The Sidi Maarouf region is crossed by national road No. 27 which connects Constantine to Jijel.

The Sidi Maarouf region and its surroundings in north-eastern Algeria are characterized by the presence of several carbonate massifs dating from the Jurassic period, such as Kef Sidi Maarouf, Kef Boulehmame, and Kef Derdja. These carbonate massifs are part of the external domain of the Maghrebian chain and are located in the transition zone between the external domain and the internal domain of the same chain, represented by the crystalline formations of the Kabyle basement. The formations in these massifs show traces of various tectonic events (fracturing, grinding, vertical layer uplift). The intense fracturing of these carbonate rocks has greatly facilitated fluid circulation, leading to the development of dissolution, karstification, dolomitization, silicification, and mineralization phenomena. The mineralized bodies forming the metallic deposits in the study areas exhibit variable morphologies and volumes. However, the most common morphologies are cluster and vein-like structures.

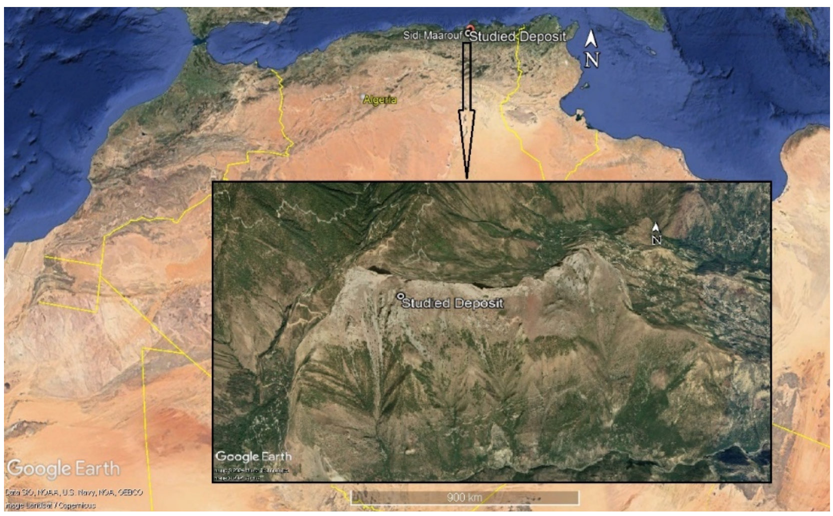


Fig. 1. Geographical location of the Sidi Maarouf deposit

The mineralization in the carbonate massifs of the Sidi Maarouf region is primarily composed of iron oxides and hydroxides (hematite, goethite, and limonite), associated with cupro-barytic mineralization.

2.2. Preparation of samples. The samples taken from the iron deposit in the Sidi Maarouf region, approximately 60 kg each are in block form. They undergo a crushing and sieving process to achieve a particle size below 5 mm. Subsequently, a series of homogenization and quartering operations are meticulously carried out to prevent any systematic errors that could compromise the results. The objective of this stage is to prepare representative samples for chemical, mineralogical, petrographic, granulo-chemical analyses, as well as other samples for enrichment experiments.

The particle size analysis was conducted using a series of sieves with mesh dimensions ranging from 4 mm to 0.045 mm; various characterizations were obtained after grinding and sieving particles below 40 µm. Iron characterization was performed using X-ray fluorescence for mass percentage determination, and the crystal structure was analyzed through X-ray diffraction.

2.3. Washing and magnetic separation of iron ore from Sidi Maarouf. After studying the results of mineralogical and chemical analyses, it is found that this product needed to be initially separated using a washing scheme and magnetic separation. Preliminary beneficiation tests through washing are applied to reduce the clay content in the iron ore from Sidi Maarouf. The product obtained through the washing process undergoes high-intensity dry magnetic separation. The performance of magnetic separation is highly dependent on the physical properties of the particles to be separated (size and magnetic nature), the quality of the applied magnetic field, and the difference in magnetic susceptibility between the separated particles.

In order to better understand the quantitative and qualitative aspects of the material, high-intensity magnetic separation enrichment tests were conducted on three particle size classes of 100 g each: –2+1 mm, –1+0.5 mm, and –0.5+0.25 mm. Each class was tested with a variation in electric current intensity from 6 to 12 Amperes, while the rotation speed was fixed at 60 rpm. The variation in electric current intensity allowed to determine the most suitable electrical intensity for achieving effective separation.

In this research work, the apparatus used is a high-intensity canister drum magnetic separator, operating under a strong magnetic field created by electromagnet coils with adjustable field intensity. This setup enables to choose the necessary intensity for maximum iron recovery.

3. Results and Discussion

3.1. Characterization of raw samples

3.1.1. Chemical composition. The results of the analysis of the chemical composition of the iron ores from Sidi Maarouf are presented in Table 1.

Table 1

Chemical analysis results of Sidi Maarouf iron ore by X-ray fluorescence (FX)

Oxides	Content (%)	Oxides	Content (%)
SiO_2	1.327	P_2O_5	0.039
Fe_2O_3	62.745	CaO	0.854
K_2O	0.016	ZnO	0.121
TiO_2	0.043	CuO	0.086
MnO	1.476	SrO	0.004
Al_2O_3	1.899	PbO	0.023
As_2O_3	0.015	L.O.I	31.134

The predominant element is Fe_2O_3, constituting more than 62 % of the composition. The content of major impurities, notably SiO_2 (1.32 %) and Al_2O_3 (1.89 %), was also assessed. The quantities of undesirable elements such as phosphorus were found to be minimal.

3.1.2. X-ray diffraction (XRD) characterization. The results of the iron phase analysis (Fig. 2) revealed that iron was primarily present in the form of goethite and hematite, with the presence of low percentages of other minerals such as calcite and orthopyroxene.

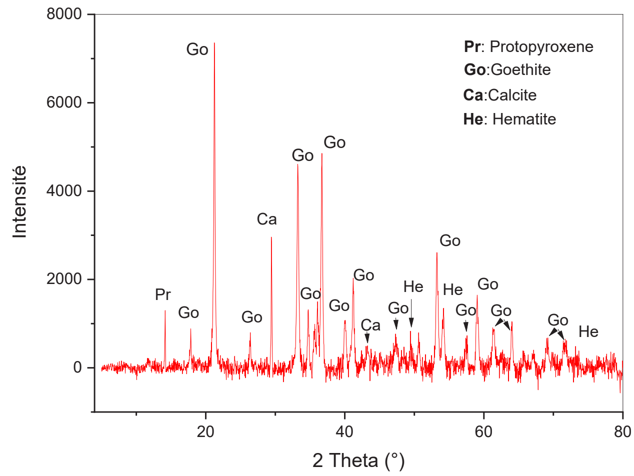
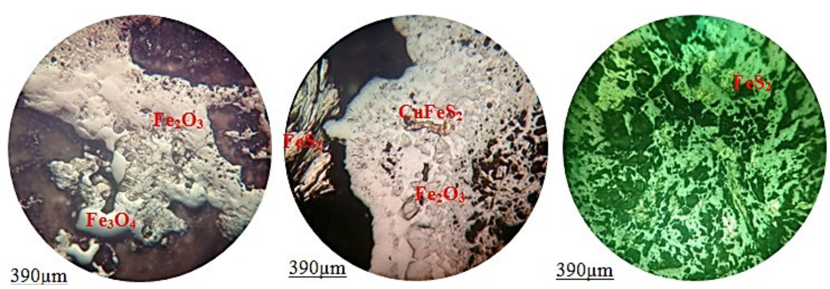


Fig. 2. X-ray diffraction spectrum of the initial sample

3.1.3. Petrographic study (thin sections). The preparation of thin sections and polished samples were carried out in the laboratory, then the analysis of polished surfaces was performed using a Leitz Optilux optical microscope (manufactured in Germany) revealed that the iron from Sidi Maarouf exhibits diverse characterization by several minerals, classified based on crystal form, size, and even the color of the grains. Observations at the scale of 390 μm allowed the identification of four distinct minerals: pyrite, hematite, magnetite, and chalcopyrite (Fig. 3).

3.1.4. Particle size analysis. The mass percentages obtained for each grain size fraction of the sandstone are gathered in Table 2. The mass fractionation shows very clearly that the majority of the overall mass of the raw ore is concentrated in the coarse fractions (+4 mm), (–4+2 mm), (–2+1 mm) and (–1+0.5 mm) evaluated at 417.92 g or 81.784 % which shows the hardness of the ore, because the rest of the product is in the minority and distributed in the fine fractions (0.5+0.25 mm), (–250+125 μm), (–125+63 μm), (–63+45 μm), (–45 μm) evaluated at 93.07 g or 17.437 %.



a *b* *c*

Fig. 3. Photograph of iron ore samples from Sidi Maarouf:
a – Photo 1: Hematite, Magnetite; *b* – Photo 2: Hematite, Pyrite, Chalcopyrite; *c* – Photo 3: Pyrite

Table 2

Results of sieving iron ore from Sidi Maarouf

Size classes (mm)	Weight (g)	Weight (%)	Yields refusing cumulative (%)	Yields passing cumulative (%)
+4	135.77	26.569	26.569	73.431
–4+2	134.98	26.415	52.984	47.016
–2+1	88.55	17.329	70.313	29.687
–1+0.5	58.62	11.471	81.784	18.216
–0.5+0.25	44.56	8.720	90.504	9.496
–0.25+0.125	44.34	8.677	99.181	0.819
–0.125+0.063	3.54	0.692	99.873	0.127
+0.063+0.045	0.47	0.091	99.964	0.036
0.045+0	0.16	0.031	99.995	0.005
Total	510.99	99.221	–	–

3.1.5. Chemical analysis of particle size slices. The obtained particle size fractions were dried, weighed, and individually subjected to chemical analysis. The detailed particle size-chemical analysis, presented in Table 3, highlights the overall acceptable quality of the iron ore. However, the significant presence of certain impurities poses a major challenge for the production of high-quality steel. The major elements, especially Fe_2O_3, show substantial variations, ranging from 53.37 % to 65.89 % by weight. In contrast, the major impurities, notably SiO_2 and Al_2O_3, considered detrimental factors in the steel industry, exhibit high concentrations, ranging from 1.27 % to 2.34 % by weight and from 1.65 % to 3.09 % by weight, respectively. These levels exceed the specified standards for high-quality steel production. To achieve the production of a satisfactory product, it becomes imperative to implement strategies for enhancing raw material value aimed at eliminating or significantly reducing these impurities. This approach, focused on improving ore purity, constitutes a crucial step in meeting the stringent requirements of the steel industry and ensuring the optimal quality of the produced steel.

3.2. Iron ore concentration

3.2.1. Washing samples. The chemical compositions of the washing products for the three samples (–2+1 mm, –1+0.5 mm, and –0.5+0.25 mm) show a slight improvement in Fe_2O_3 up to 64 % and do not significantly reduce undesirable impurities compared to the raw samples. There is a noticeable decrease in silica and clay impurity, with the SiO_2 content decreasing from 1.4 % to 1.17 % in the washed ore, and similarly, the Al_2O_3 content decreases from 2.07 % to 1.89 %. The results are presented in Table 4.

3.2.2. Dry magnetic separation of washed iron fractions. The field intensity is a crucial parameter in this process, as it exerts a significant influence on the attraction of the magnetic particle [12]. The intensities used in this experimental phase range from 6 to 12 Amperes with a 2 A interval between each pass. The test carried out consisted of examining the effect of the intensity of the magnetic field on the behavior of a specific magnetic particle. The data collected clearly demonstrated a positive correlation between the increase in magnetic field intensity and the attraction of the particle. This result highlights the fundamental importance of magnetic field strength in the control and manipulation of magnetic particles. By deepening our understanding of this relationship, it becomes evident that the magnetic field intensity acts as a key parameter to modulate the interaction between the magnetic field and the magnetic particle. Higher magnetic field intensity generates a stronger attractive force, which can be attributed to the intrinsic properties of the magnetic material used.

Table 3

Results of chemical analyzes of the different particle size ranges

Size classes (mm)	Chemical Composition (%)											
	SiO_2	Fe_2O_3	Al_2O_3	CaO	K_2O	TiO_2	MnO	CuO	P_2O_5	ZnO	PbO	L.O.I
+4	1.27	63.10	1.65	0.49	0.04	0.03	1.1	0.07	0.01	0,01	0.031	31.89
–4+2	1.29	61.57	1.89	1.03	0.03	0.03	1.22	0.05	0.02	0,01	0.08	32.61
–2+1	1.56	63.03	2.3	1.33	0.03	0.08	2.27	0.02	0.03	0,09	0.01	28.16
–1+0.5	1.4	63.78	2.07	1.11	0.01	0.05	1.76	0.02	0.07	0,01	0.01	30.37
–0.5+0.25	1.65	57.09	2.4	1.36	0.05	0.08	2.17	0.03	0.03	0,05	0.02	34.81
–0.25+0.125	2.21	61.4	2.99	1.71	0.11	0.09	2.7	0.05	0.1	0.01	0.006	28.47
–0.125+0.063	2.34	58.94	3.09	1.57	0.12	0.09	2.55	0.02	0.06	0.009	0.003	32.13
+0.063+0.045	1.73	53.37	2.35	1.17	0.08	0.07	4.83	0.02	0.04	0.008	0.003	38.87
0.045+0	1.82	55.89	2.44	1.18	0.05	0.06	2.24	0.02	0.05	0.01	0.003	26.17

Table 4

Results of chemical analyzes of samples treated by washing

Size classes (mm)	Chemical Composition (%)											
	SiO_2	Fe_2O_3	Al_2O_3	CaO	K_2O	TiO_2	MnO	CuO	P_2O_5	ZnO	PbO	L.O.I
–2+1	1.441	63.879	2.102	0.913	0.02	0.039	1.372	0.01	0.021	0.081	0.036	21.303
–1+0.5	1.177	64.432	1.899	0.972	0.016	0.052	1.769	0.01	0.032	0.095	0.017	29.277
–0.5+0.25	1.205	61.232	2.051	1.047	0.03	0.063	2.013	0.02	0.038	0.11	0.012	28.517

The experimental results indicate that Fe_2O_3 increases progressively for different particle size ranges, highlighting the influence of field intensity. They yielded Fe_2O_3 contents ranging from 63 % to 67 %. The maximum attraction is achieved for a particle size in the diameter range of 1 mm to 0.5 mm, with a content of 67.7 % and an intensity of 12 A. The variation in silica content shows a decreasing trend in the three considered fractions (Fig. 4). For the particle size fraction −2+1 mm, the SiO_2 content decreases from 1.35 % to 1.17 %, compared to an initial feed of 1.44 %. In the case of the −1+0.5 mm fraction, the contents vary in the range of 1.09 % to 0.92 %, compared to the initial content of 1.17 % in the washed sample. For the lower size fraction of 0.5 mm, a steady decrease in silica content is observed.

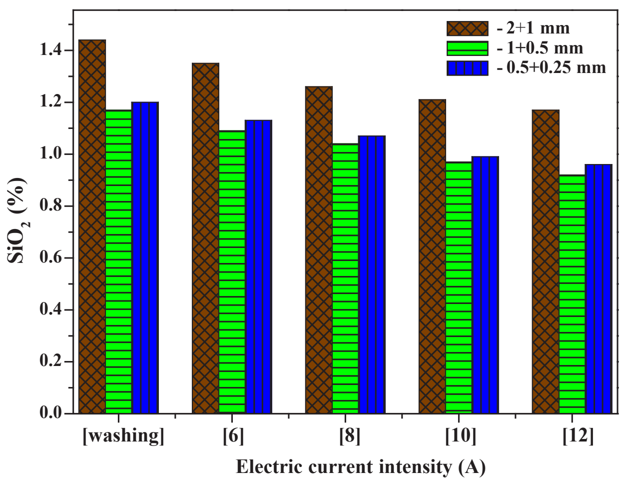


Fig. 4. Impurity distribution of (SiO_2) as a function of field intensity

The results indicate a decrease in Al_2O_3 contents following high-intensity magnetic separation. The (−1+0.5) fraction exhibits the lowest Al_2O_3 content, decreasing from 0.89 % to 0.77 %. This reduction represents a decrease of over 20 % compared to the washed iron samples (Fig. 5). A similar trend is observed for other enriched particle size classes.

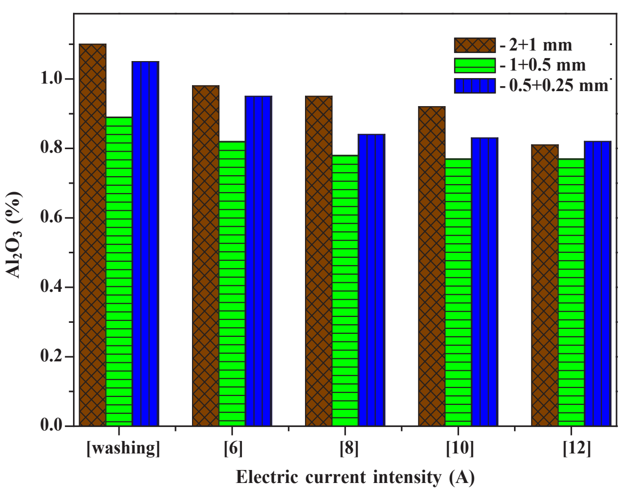


Fig. 5. Impurity distribution of (Al_2O_3) as a function of field intensity

3.2.3. Proposed scheme for the preparation and enrichment of iron ore from Sidi Maarouf. After a thorough analysis of contemporary iron ore beneficiation schemes for Sidi Maarouf (Fig. 6), it became apparent that our approach will primarily focus on concentration techniques that optimize the ore's properties. At the first level, ore preconditioning involves various operations of preparation and particle size classification tailored to grain dimensions for efficient enrichment. The number and arrangement of these operations will be specified during experimental trials. The second level of enrichment includes high-intensity magnetic separation (HIMS) aimed at achieving maximum iron recovery. This will be accomplished using a conventional circuit separator, such as an electromagnet, with adjustable field intensity. This flexibility will allow to choose the necessary intensity, considering that the ore to be separated is hematite with low magnetic susceptibility.

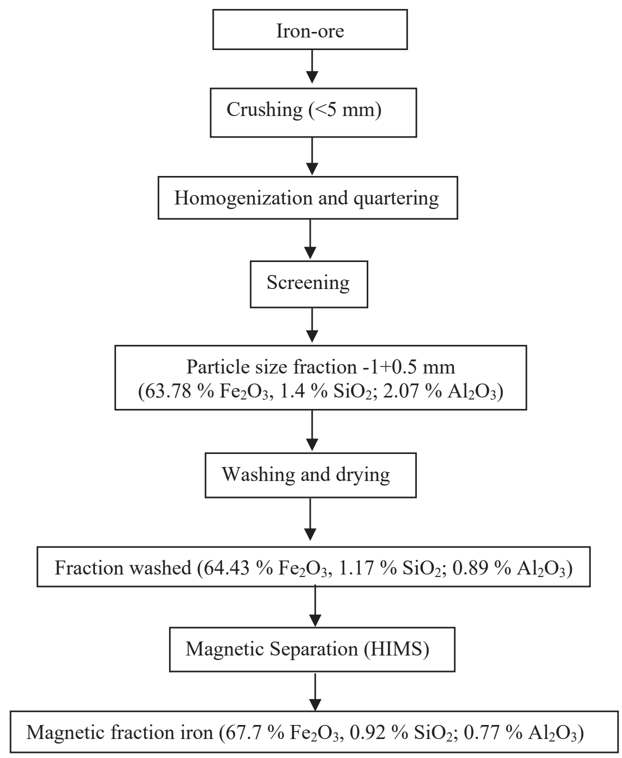


Fig. 6. Proposed scheme for the preparation and enrichment of iron ore from Sidi Maarouf

3.3. Limitations and directions of research development. Magnetic separation is a widely used technique in the processing of iron ores to extract magnetic particles from raw ores. However, this method has certain limitations. Iron ore beneficiation methods using magnetic processes are continually dependent on a level of efficiency and performance, both in terms of equipment and ore property characterization, including the precise identification of the ore. Optimizing these processes requires a thorough understanding of mineralogical characteristics, physical and chemical properties of minerals, and technologies used to ensure effective separation. Magnetic separation may be less effective for fine particles, as they tend to behave in a non-magnetic manner, making it challenging to capture them with magnetic fields.

When applying magnetic separation, it is important to note that it does not always completely eliminate all non-magnetic impurities present in the ore. Therefore, to achieve the purity levels required for the final product, it may be imperative to combine magnetic separation with other separation methods, such as flotation, gravity, or emerging technologies, to enhance the overall efficiency of the process.

4. Conclusions

The following conclusions can be drawn from the beneficiation of the iron deposits in Sidi Maarouf:

The particle size analysis of the ore revealed that the majority of the overall mass of the raw ore concentrates in the coarse fractions, indicating that the iron ore from Sidi Maarouf is inherently coarse.

Chemical analyses conducted on the representative sample taken from the studied area indicate a strong presence of hematite. However, notable levels of quartz and clay impurities are also observed, negatively impacting the quality of steel products.

XRD analysis of the raw sample shows that the majority of peaks are attributed to hematite and goethite, with the presence of calcite and proto-pyroxene also noted.

Petrographic study reveals a mineralogical association composed of hematite, magnetite, and pyrite with traces of chalcopyrite.

Detailed granulo-chemical analysis highlights that the particularly iron-rich class (63.78 % Fe_2O_3) is found in the particle size range between −1+0.5 mm.

Magnetic separation of different classes (−2+1 mm), (−1+0.5 mm), and (−0.5+0.25 mm) with alternating amperages (6 to 12 A) shows that the experiment conducted in the (−0.5+0.25 mm) class at 12 A offers a higher iron concentration (67.7 % Fe_2O_3), accompanied by lower silica (0.92 % SiO_2) and alumina (0.77 % Al_2O_3) impurity content, resulting in a product suitable for the steel industry.

Acknowledgements

The authors express their gratefully acknowledgements to all colleagues from the Laboratory of Mining Resources Valorization and Environment (*LAVAMINE*), Mining Department, Badji Mokhtar University-Annaba, Algeria, as well as to colleagues form the Institute of Architecture and Earth Sciences (University of Ferhat Abbes-Setif) for their assistance to carry out this research study.

Conflict of interest

The authors declare that they have no conflict of interest concerning this research, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The paper has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Zerzour, O., Gadri, L., Hadji, R., Mebrouk, F., Hamed, Y. (2020). Semi-variograms and kriging techniques in iron ore reserve categorization: application at Jebel Wenza deposit. *Arabian Journal of Geosciences, 13 (16)*. doi: https://doi.org/10.1007/s12517-020-05858-x
2. Filippov, L. O., Severov, V. V., Filippova, I. V. (2014). An overview of the beneficiation of iron ores via reverse cationic flotation. *International Journal of Mineral Processing, 127,* 62–69. doi: https://doi.org/10.1016/j.minpro.2014.01.002
3. Selim, K. A., Rostom, M. (2018). Bioflocculation of (Iron oxide – Silica) system using Bacillus cereus bacteria isolated from Egyptian iron ore surface. *Egyptian Journal of Petroleum, 27 (2),* 235–240. doi: https://doi.org/10.1016/j.ejpe.2017.07.002
4. Xiong, D., Lu, L., Holmes, R. J. (2015). Developments in the physical separation of iron ore: magnetic separation. *Iron ore*. Woodhead Publishing, 283–307.
5. Suthers, S. P., Nunna, V., Tripathi, A., Douglas, J., Hapugoda, S. (2014). Experimental study on the beneficiation of low-grade iron ore fines using hydrocyclone desliming, reduction roasting and magnetic separation. *Mineral Processing and Extractive Metallurgy, 123 (4),* 212–227. doi: https://doi.org/10.1179/1743285514y.0000000067
6. Nadir, D. E. G. H. F. E. L., Chouki, F. A. R. S. I., Azzedine, B. E. N. Y. A. H. I. A., Moussa, Z. A. O. U. I. (2021). Evaluation of materials from the excavation of the Ouenza hematite deposit (North-East Algeria) by gravimetric enrichment. *Natural Volatiles & Essential Oils, 8 (4),* 11529–11537.
7. Zhang, X., Gu, X., Han, Y., Parra-Álvarez, N., Claremboux, V., Kawatra, S. K. (2019). Flotation of Iron Ores: A Review. *Mineral Processing and Extractive Metallurgy Review, 42 (3),* 184–212. doi: https://doi.org/10.1080/08827508.2019.1689494
8. Rath, S. S., Sahoo, H. (2020). A Review on the Application of Starch as Depressant in Iron Ore Flotation. *Mineral Processing and Extractive Metallurgy Review, 43 (1),* 122–135. doi: https://doi.org/10.1080/08827508.2020.1843028
9. Sis, H., Karaağaç, T., Birinci, M., Kiyak, T. (2021). Düşük tenörlü manyetit cevherinin manyetik ayirma ve yerçekimi ile zenginleştirilmesi: tane boyu etkisi. *Bilimsel Madencilik Dergisi, 60 (1),* 31–39. doi: https://doi.org/10.30797/madencilik.796806
10. Akbari, H., Noaparast, M., Shafaei, S. Z., Hajati, A., Aghazadeh, S., Akbari, H. (2018). A Beneficiation Study on a Low Grade Iron Ore by Gravity and Magnetic Separation. *Russian Journal of Non-Ferrous Metals, 59 (4),* 353–363. doi: https://doi.org/10.3103/s1067821218040028
11. Siame, M., Kaoma, J., Shibayama, A. (2021). Development of impurities removal process for low-grade Sanje iron ore using mineral processing technologies. *Journal of Natural and Applied Sciences, 3 (1),* 36–52. doi: https://doi.org/10.53974/unza.jonas.3.1.460
12. Nameni, A., Nazari, M., Shahmardan, M. M., Nazari, M., Mashayekhi, V. (2022). Separation and trapping of magnetic particles by insertion of ferromagnetic wires inside a microchip: Proposing a novel geometry in magnetophoresis. *Journal of Magnetism and Magnetic Materials, 560,* 169424. doi: https://doi.org/10.1016/j.jmmm.2022.169424

Abdeslam Chaib, *PhD, Lecturer, Head of Mining Department, Laboratory of Valorisation of Mining Resources and Environment (LAVAMINE), Badji Mokhtar University, Annaba, Algeria, ORCID: https://orcid.org/0009-0002-9778-013X*

Soufiane Bouabdallah, *PhD, Lecturer, Abderrahmane Mira University, Bejaia, Algeria, ORCID: https://orcid.org/0000-0002-8540-093X*

Meriem Ferfar, *PhD, Researcher, Environmental Research Center (C.R.E), Annaba, Algeria, ORCID: https://orcid.org/0000-0002-2028-5213*

✉***Aissa Benselhoub,*** *Associate Researcher, Environment, Modeling and Climate Change Division, Environmental Research Center (C.R.E), Annaba, Algeria, e-mail: benselhoub@yahoo.fr, ORCID: https://orcid.org/0000-0001-5891-2860*

Nadiia Dovbash, *Researcher, National Scientific Centre «Institute of Agriculture of the National Academy of Agricultural Sciences», Chabany, Ukraine, ORCID: https://orcid.org/0000-0002-4741-2657*

✉***Stefano Bellucci,*** *Senior Researcher, INFN-Laboratori Nazionali di Frascati, Frascati, Italy, e-mail: bellucci@lnf.infn.it, ORCID: https://orcid.org/0000-0003-0326-6368*

✉*Corresponding author*