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Enhancing Iron Separation and Recovery from Egyptian Banded Iron Formation Using Paper Industry Sludge: A Sustainable Reduction Roasting Approach

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Abstract

This paper proposes an innovative method to upgrade Um Nar Banded Iron Formation (BIF). The method consists of three stages: reduction roasting using paper industry sludge and sawdust, sulfuric acid leaching, and magnetic separation. The effects of $CaCO_3$/sawdust concentration and magnetic field intensity were examined. This approach not only provides an effective means of processing complex and low-grade iron ores but also offers a sustainable solution for recycling industrial waste. Additionally, it utilizes biomass sawdust as a green reducing agent, a new type of clean energy source with low sulfur content, which does not pollute the environment. Adding paper industry sludge as calcium carbonate ($CaCO_3$) led to its reaction with Si and Al minerals, forming grossular ($Ca_3Al_2(SiO_4)_2(OH)_4$). This prevented SiO_2 from reacting with iron oxides, thereby enhancing iron recovery. The resulting iron concentrate meets the quality standards necessary for steel production. The iron concentrate obtained through this method, i.e. reduction roasting conducted with 10% dosage of reductant, followed by acid leaching and magnetic separation at 2000 gauss, contains 67.23% total Fe and 1.5% SiO_2 with a total Fe recovery of 73.82%, meeting the iron ore quality requirements of the steel and iron industry.

Keywords:
Um Nar, BIF; reduction roasting; biomass-sawdust; calcium carbonate; paper industry sludge

1. Introduction

Reduction roasting offers several advantages over physical beneficiation techniques, including enhanced iron recovery and the ability to process iron ores with poor liberation (**Roy et al., 2020**). This process uses carbonaceous reductants to convert iron oxides such as hematite and goethite into magnetite, a ferromagnetic product that can be separated from other materials by low-intensity magnetic separation. The roasting process creates fractures in the ore, facilitating liberation during grinding (**Zhu et al., 2010**). Traditionally, coal and coke have been the primary reductants for iron ores. However, with the depletion of high-grade coal reserves, there is a need to develop alternative reductants. Waste biomass is being considered as a promising alternative due to its significant volatile carbonaceous content, which generates gases such as CH_4, H_2, CO_2, and CO that can reduce iron oxides. Additionally, biomass produces substantial heat, accelerating the reduction process (**Roy et al., 2020**). Numerous studies have confirmed that biomass is a viable substitute for fossil fuels like coal, coke and natural gas, serving as a nontoxic and renewable solid fuel (**Liu et al., 2017; Zhang et al., 2017; Salatino & Solimene, 2017**). Researchers have successfully used biomass as reductants for iron in several studies, employing materials such as charcoal from sawdust, nutshell, waste biomass (**Cheng et al., 2016; Das et al., 2024**), and raw biomass like pine sawdust (**Huang et al., 2016; Wei et al., 2016; Qiu et al., 2023**), coconut shell waste (Nayak et al., 2019), and corn straw (**Zhao et al., 2019; Zhang et al., 2023**).

Banded Iron Formation (BIF) is a thinly layered sedimentary rock composed primarily of silica and iron minerals, believed to be an original chemical precipitate modified by diagenesis and metamorphism (**James & Trendall, 1982**). The total ore reserves of BIFs in the Eastern Desert-Egypt are 53 Mt, which are not utilized at present due to their high SiO_2 content (**Dardir, 1990**). **Hussein (1998)** conducted a review of Egyptian Banded Iron Formations and reported iron composition ranging from 31.9% to 52.3% and silica from 19.3% to 32.4%. The Um Nar BIF, a prominent example in Egypt, represents one of the largest iron formation deposits within the Pan-African rocks of the Eastern Desert, with an estimated 13.7 million tons of mineable reserves (**Attia, 1950**). Currently, there are no commercial mining opera-

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tions at the Um Nar site due to the high silica content. The main objective of this study is to thoroughly investigate the influence of paper industry sludge (as a source of calcium carbonate) and sawdust on the reduction roasting process of Um Nar BIF, and to evaluate its effectiveness in separating and recovering iron.

2. Material and methods

2.1. Materials

The sample used in this study is a BIF iron ore from the Um Nar locality in the Eastern Desert of Egypt, located at latitude 25° 15' 29.3" N and longitude 34° 15' 49.7" E. The ore was crushed using a jaw crusher and a roll crusher, then ground with a dry ball mill until the particle size was finer than 75 microns. The ground sample was thoroughly mixed and homogenized, then divided into smaller portions and sealed in plastic bags for later use.

The biomass utilized in the experiments was sawdust from beech pine wood, serving as a green reducing agent. This biomass was obtained as a byproduct from wood processing industries, including sawmills, furniture manufacturing and carpentry, specifically sourced from a local timber wood-shop in Qena, Egypt (see **Figure 1**). The sawdust was used without any further treatment, and the particle size was below 1 mm. Calcium carbonate ($CaCO_3$) from paper industry sludge was employed as a green roasting additive. The calcium carbonate was supplied by the Quena Paper Industry Company (QPIC), which manufactures newsprint, printing and writing papers from bagasse (see **Figure 2**).

Figure 1: A composite photograph of sawdust from multiple wood shops (* indicates the actual sawdust sample used in the experiments)

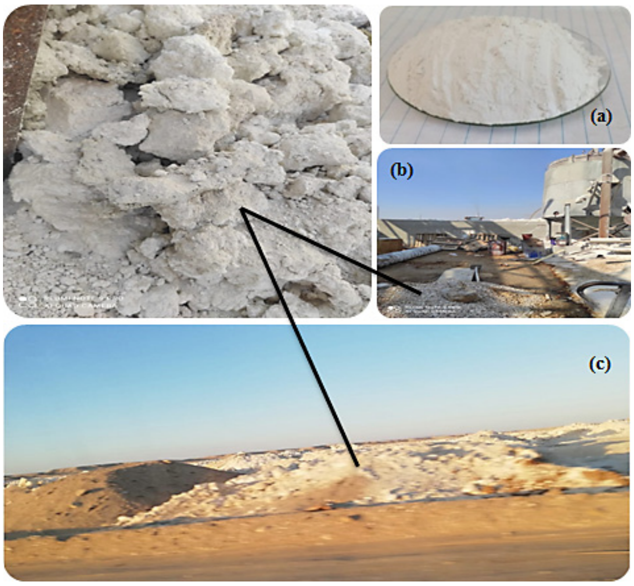

Figure 2: a) Paper industry sludge (calcium carbonate waste) after being ground in a mortar, b) Calcium carbonate waste within the Quena Paper Industry Company, c) Quena Paper Industry Company sludge dump abroad.

2.2. Methods

2.2.1. Characterization of the ore sample

Several qualitative and quantitative analysis techniques were employed to characterize the ore sample. The chemical composition was analyzed using X-ray fluorescence (XRF) with a Philips PW 2404 instrument from the Netherlands. The morphology and elemental chemical composition of the head sample was determined respectively by scanning electronic microscopy (SEM) using secondary electrons detector and energy dispersive X-ray analysis (EDS). The mineral composition was determined using X-ray diffraction (XRD) with a Philips type 1710 XRD unit (λ = 1.54060 Å) within a 2θ range of 5° to 80°. The mineral phases were identified using X'Pert High Score Plus and Origin software. For routine chemical analysis, total iron (Fe) and silicon dioxide (SiO_2) were measured through wet chemical methods. This involved dissolving the samples using hydrochloric and nitric acids before reduction process, while using fusion technique after reduction. Iron content was quantified via complexometry using salicylic acid as an indicator and EDTA as the titrant, while silica was measured gravimetrically using the double backing method.

For petrographic analysis, a thin section of the Um Nar BIF ore sample was prepared and examined using a polarizing microscope (Leitz Orthoplan). A rock-cutting machine was initially used to obtain a hand specimen of the ore, which was then mounted and polished. The polished specimen was subsequently examined under a microscope equipped with a camera and PC workspace software to capture images and study its mineralogical and textural characteristics.

2.2.2. Characterization of the reductant

The behavior of sawdust upon heating was assessed through proximate analysis, which quantified the amounts of gas, tar and vapor released, as well as the

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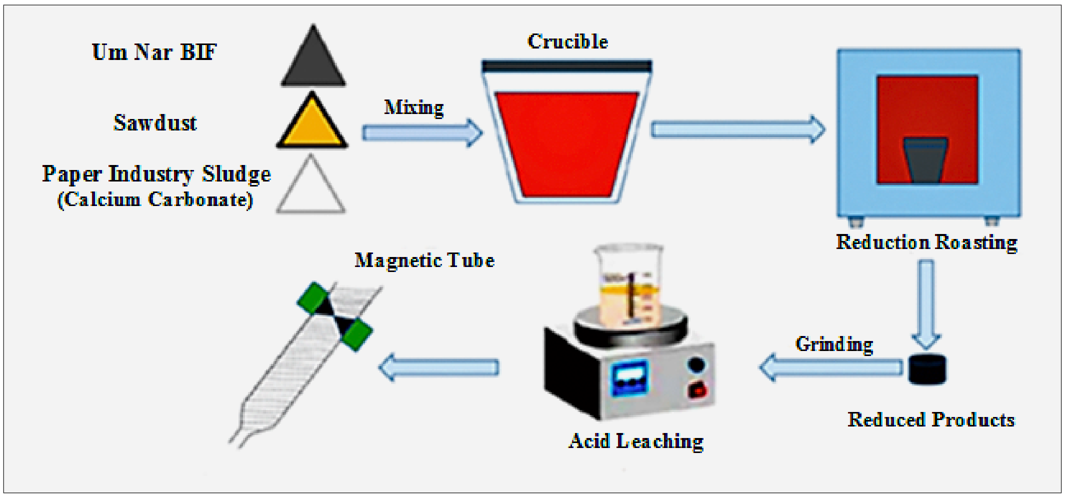

Figure 3: Graphical abstract for the experimental work

fixed carbon remaining. This analysis was performed according to the standards of the American Society for Testing and Materials (ASTM) (**American Society for Testing and Materials, 1984**). The elemental composition of the sawdust was determined using ultimate analysis with a PerkinElmer 2400 Series II CHNS/O Analyzer. The chemical composition of calcium carbonate ($CaCO_3$) from paper industry sludge was analyzed by X-ray fluorescence (XRF) to assess its oxide fractions, and its mineral composition was identified through X-ray diffraction (XRD).

2.2.3. Experimental work

The experimental work was conducted in three stages (see **Figure 3**): first, the reduction roasting of a mixture of BIF, sawdust and paper industry sludge; second, the acid leaching of the roasted ore; and third, the magnetic separation of the leached ore.

2.2.3.1. Reduction roasting experiments

Reduction was carried out in a muffle furnace maintained at 800°C for about 30 minutes. The amount of $CaCO_3$ and sawdust was varied (5%, 10%, 15% and 20% by weight of the sample). The weight ratio of sawdust to $CaCO_3$ sludge was 1:1, as adopted from **Gade et al. (2015)**. After reduction, the crucible was removed from the furnace, cooled to room temperature, and quenched in water to stop further chemical changes and wash off unconsumed carbon. The sample was then dried in a vacuum oven at 120°C for about 2 hours until its weight stabilized. The roasted ore was ground to 200 mesh using an agate mortar.

2.2.3.2. Acid leaching experiments

The ground (roasted) ore was then leached with diluted sulfuric acid in a 500 ml beaker placed on a magnetic stirrer set to 300 rpm. The leaching experiment was conducted under the following optimized conditions (**Wu et al., 2019**): 0.7 mol/L sulfuric acid concentration, 5 minutes leaching time, 60°C leaching temperature, and a 10:1 liquid-to-solid ratio. After leaching, the leached ore was collected for the third step, wet low-intensity magnetic separation (WLMS).

2.2.3.3. Magnetic separation experiments

After the leaching process, the samples were subjected to magnetic separation. A 20 g sample of the leached product was fed as a slurry into a Davis tube with the magnetic field activated. The Davis tube operating conditions were as follows: magnetic field intensity from 700 to 2000 gauss, tube axis inclination of 22° from horizontal, oscillation rate of 64 cycles per minute and wash water rate of 400 cm^3 per minute for 15 minutes. Clean separation was achieved in five minutes, after which the tube was stopped and a constant water current was allowed to flow co-currently to wash the specimen. The non-magnetic fraction was collected in a container. The magnetic field was then switched off to release the concentrate into a clean container. Both magnetic and non-magnetic products were filtered, dried, weighed and chemically analyzed.

The grade and recovery of total iron (Fe) were used to evaluate the results of the proposed route, calculated using the following **Equations 1** and **2**.

$$C,\% = \frac{M_{EDTA} \cdot V_{EDTA} \cdot M_{Fe} \cdot V_{Dissolve\ sample} \cdot 100}{W_{sample} \cdot 1000 \cdot V_{sample}} \quad (1)$$

$$R,\% = \frac{C\ c}{F\ f} \times 100 \quad (2)$$

where: c, (%) is the iron grade in the magnetic iron concentrate; M_{EDTA}, (mol/L) is the molarity of EDTA solution; V_{EDTA}, (mL) is the volume of EDTA solution used in titration; M_{Fe}, (55.845 g/mol) is the molar mass of iron; $V_{Dissolve\ sample}$, (mL) is the volume of the dissolved sample solution; W_{Sample},(g) is the weight of the sample being analyzed; V_{Sample}, (mL) is the volume of the sample

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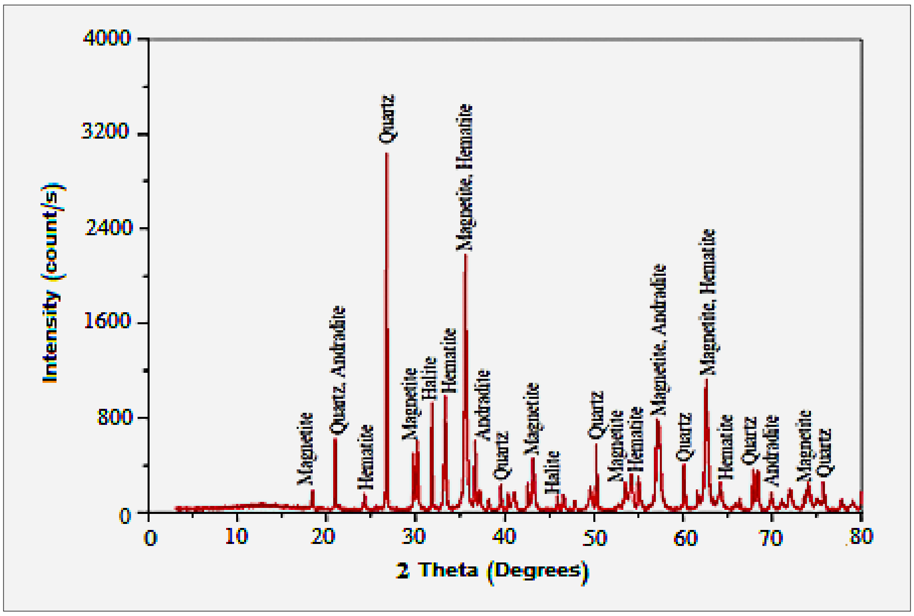

Figure 4: X-Ray diffraction analysis of the Um Nar BIF head sample

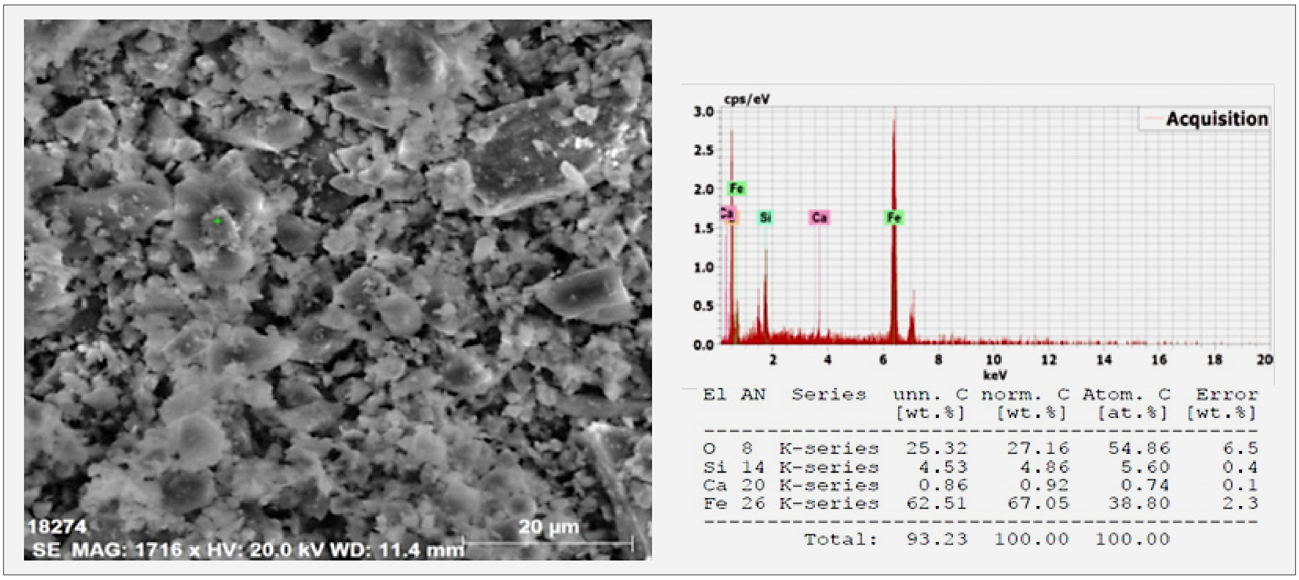

Figure 5: SEM-EDS results of the feed sample (Um Nar BIF)

Table 1: XRF analysis of the Um Nar BIF head sample

Constituents	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	Cl	P_2O_5	SO_3	Cr_2O_3	Ag_2O	LOI
Grade, %	25.00	1.17	64.50	6.75	0.40	0.26	0.11	0.05	0.03	1.38	0.23	0.06	0.03	0.03

solution used in titration; R, (%) is the recovery of iron; f, (%) is the iron grade in the feed; C, (%) is the mass of the magnetic concentrate and F, (%) is the total mass of the feed used in the magnetic separation process.

3. Results and discussion

3.1. Ore sample characterization

The XRD analysis results revealed that the primary mineral phases were quartz and iron oxides. Additionally, halite and andradite were identified as associated minerals, as illustrated in **Figure 4**. **Figure 5** represents the SEM-EDS results of the feed sample. The SEM-EDS results revealed that the main chemical compositions in the prism structure were Fe, Si and O. The head sample was analyzed using XRF, with the results presented in **Table 1**. The analysis showed that the sample contains 25% SiO_2 and 64.50% Fe_2O_3 (equivalent to 45.10% total Fe).

Microscopic analysis, as shown in **Figure 6**, reveals that the rock is very fine to medium-grained and primarily composed of iron oxides, quartz, magnesioferrite and

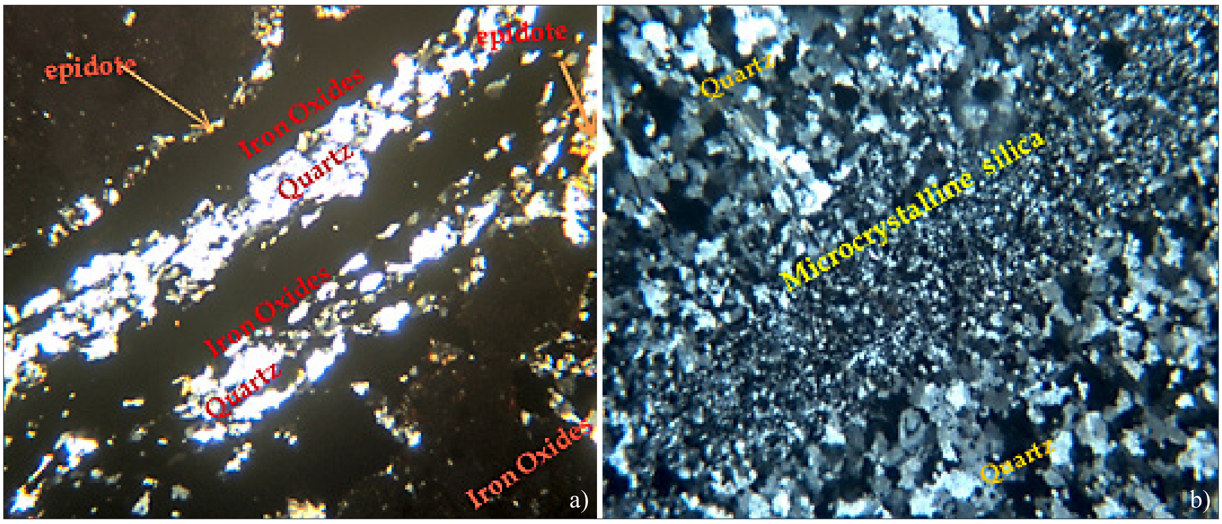

Figure 6: Photomicrographs of thin section (a) showing the alternating bands of segregation composed of quartz (white) and other silicate minerals alternating with iron oxides (black) and other mafic mineral (b) revealing the presence of microcrystalline silica (25X, C.N).

epidote, with minor amounts of microcrystalline silica, sericite, biotite, chlorite and carbonates. The iron oxides and magnesioferrite minerals form very fine to medium-grained aggregates, creating nearly parallel bands interspersed with quartz and epidote, and filling the interstitial spaces between quartz grains. The rock exhibits significant deformation and alteration of its essential mineral constituents. As a result of stress and deformation processes, quartz and other minerals are stretched and have sutured outlines.

3.2. Reductant characterization

The results of proximate and ultimate analyses of the sawdust sample are presented in **Tables 2** and **3**. The proximate analysis, performed according to ASTM standards, reveals that the sawdust has a moisture content of 3.05% and an ash content of 1%. The volatile matter and fixed carbon contents are 82.95% and 13.0%, respectively. The ultimate analysis indicates that the sawdust mainly contains carbon and hydrogen, which are essential gases for driving the reduction process. The presence of these gases ensures the effectiveness of the reduction process. The total sulfur content in the sawdust is 0.19%, which is within acceptable limits. Additionally, the sawdust has a high calorific value of 5758 kcal/kg.

The XRD analysis of the paper industry sludge revealed that calcite ($CaCO_3$) is the predominant mineral

Table 2: Proximate analyses test result for sawdust

Components	Value, %
Ash	1.00
Moisture	3.05
Volatile matter	82.95
Fixed carbon	13.00

Table 3: Ultimate analyses result for sawdust

Elements	Value, %
Carbon	50.70
Hydrogen	8.24
Nitrogen	1.10
Sulfur	0.19
Oxygen, (by diff.)	39.77
Heating Value	5758 kcal/kg

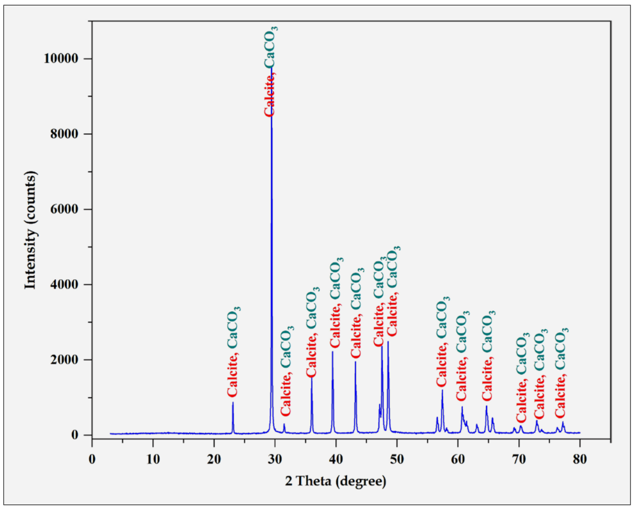

Figure 7: X-Ray diffraction analysis of the paper industry sludge

Table 4: Chemical composition of the paper industry sludge ($CaCO_3$)

Constituents	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	Cl	SO_3	LOI
Grade %	4.20	0.43	0.12	**52.23**	0.24	0.02	0.03	0.05	0.01	0.01	41.19

Table 5: The results of sample analysis after individual processing stages

$CaCO_3$ and Sawdust Concentration, %	Feed mixture of ore sample and reductant		Roasted ores				Leached ores				Magnetic separation concentrates			
	Tot. Fe, %	SiO_2, %	Tot. Fe, %		SiO_2, %		Tot. Fe, %		SiO_2, %		Tot. Fe, %		SiO_2, %	
	Grade	Grade	Grade	Recovery	Grade	Recovery	Grade	Recovery	Grade	Recovery	Grade	Recovery	Grade	Recovery
5	46.23	24.60	46.27	95.56	24.60	95.48	46.20	85.13	24.50	84.85	65.09	78.05	2.00	4.51
10	45.90	24.40	45.92	92.62	24.40	92.58	45.87	85.12	24.26	84.68	67.23	73.81	1.54	3.18
15	43.60	24.00	43.57	89.39	24.23	90.31	43.57	84.08	24.00	83.49	67.55	68.24	1.34	2.46
20	43.35	23.90	43.45	87.63	23.66	86.55	42.96	82.57	23.30	81.22	67.68	64.12	0.57	0.97

phase, as illustrated in **Figure 7**. The oxide composition of the paper industry sludge ($CaCO_3$) was determined using XRF, and the results are presented in **Table 4**.

3.3. Effect of the Concentration of the Calcium Carbonate and Sawdust Mixture

Table 5 shows the results of sample analysis after individual processing stages. **Figure 8** illustrates the impact of dosage of the mixture of $CaCO_3$ and sawdust on the magnetic separation process. The leaching and magnetic separation conditions are described in the subsection 2.2.3 Experimental work. The data reveal that increasing the dosage of the mixture of $CaCO_3$ and sawdust enhances the total Fe grade of the iron concentrate. However, this increase in grade is practically negligible with an increase in the reductant dosage from 10% to 15% or 20%. Specifically, as the reductant dosage increases from 5% to 10%, the total Fe grade rises from 65.09% to 67.23%, while with a further increase in the reductant dosage, to 15% and 20%, the total Fe grade increases by only 0.32% and 0.45% respectively (i.e. to 67.55% and 67.68%). The significantly higher increase in Fe grade with increasing reductant dosage from 5% to 10% is due to more efficient iron oxide reduction. At reductant dosages of 15% and 20%, further improvement of Fe grade is negligible, likely because the system is saturated and side reactions or inefficiencies limit the effect. The silica content decreases from 2.00% to 0.57% as the reductant dosage increases from 5% to 20%. Additionally, increasing the reductant dosage from 5% to 20% results in a decrease in the total Fe recovery from 78.05% to 64.12%. Therefore, a 10% dosage of the mixture of $CaCO_3$ and sawdust is recommended. At this dosage, a high total Fe grade and recovery were achieved while minimizing the silica grade in the concentrate.

The total Fe grade and Fe recovery in the magnetic concentrates are significantly influenced by the CO concentration, which can be either insufficient or excessive (**Li et al., 2021**). At lower dosages (5-10%), the formation of CO gas through the decomposition of $CaCO_3$ and the reduction of carbon (**Equations 3** and **4**) provides a favorable environment for the reduction of hematite (Fe_2O_3) to magnetite (Fe_3O_4) (**Equation 5**). Magnetite is more easily separated by magnetic methods, resulting in higher Fe recovery and grade. However, at higher dosages (above 10%), there is a risk of over-reduction, leading to the formation of wustite (FeO) (**Equation 6**). Wustite, being less magnetic than magnetite, is more difficult to separate, which explains the observed significantly smaller increase in Fe grade with an increase in reductant dose from 10% to 15% or 20% than with an increase from 5% to 10%, as well as a further significant decline in Fe recovery with increases in reductant dosage to 15% and 20%. This phenomenon is confirmed by XRD analysis of reduced Um Nar BIF under different dosages of the mixture of $CaCO_3$ and sawdust (see **Figure 9**), which shows an increase in wustite content with higher reductant dosages.

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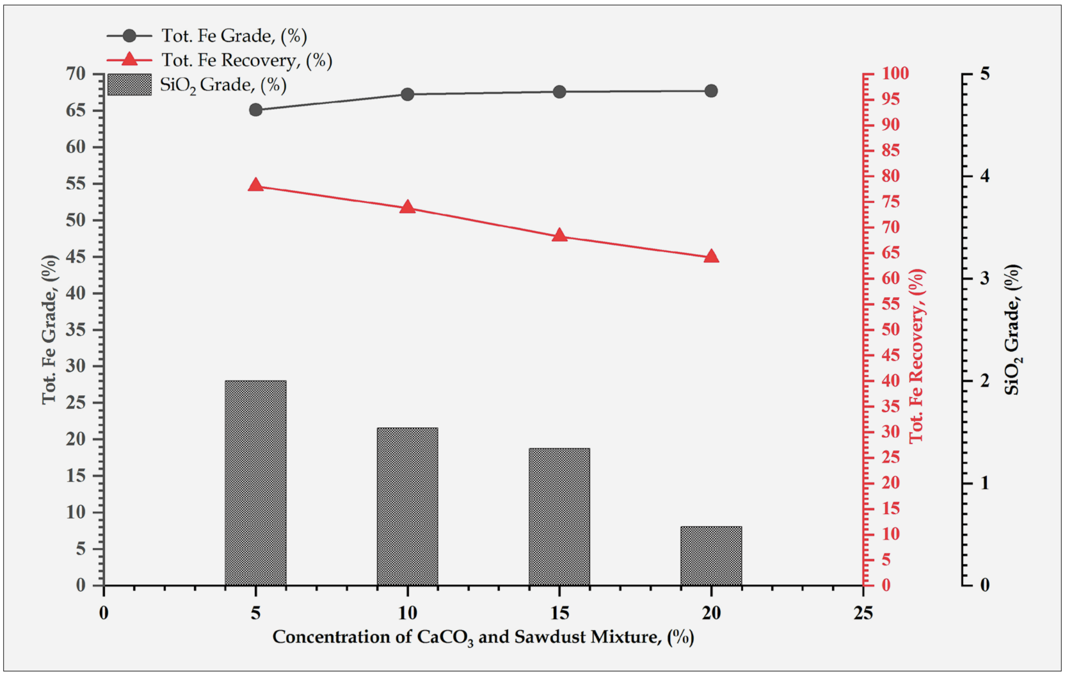

Figure 8: Effect of CaCO3 and sawdust mixture concentration on tot. iron grade, tot. iron recovery and silica content

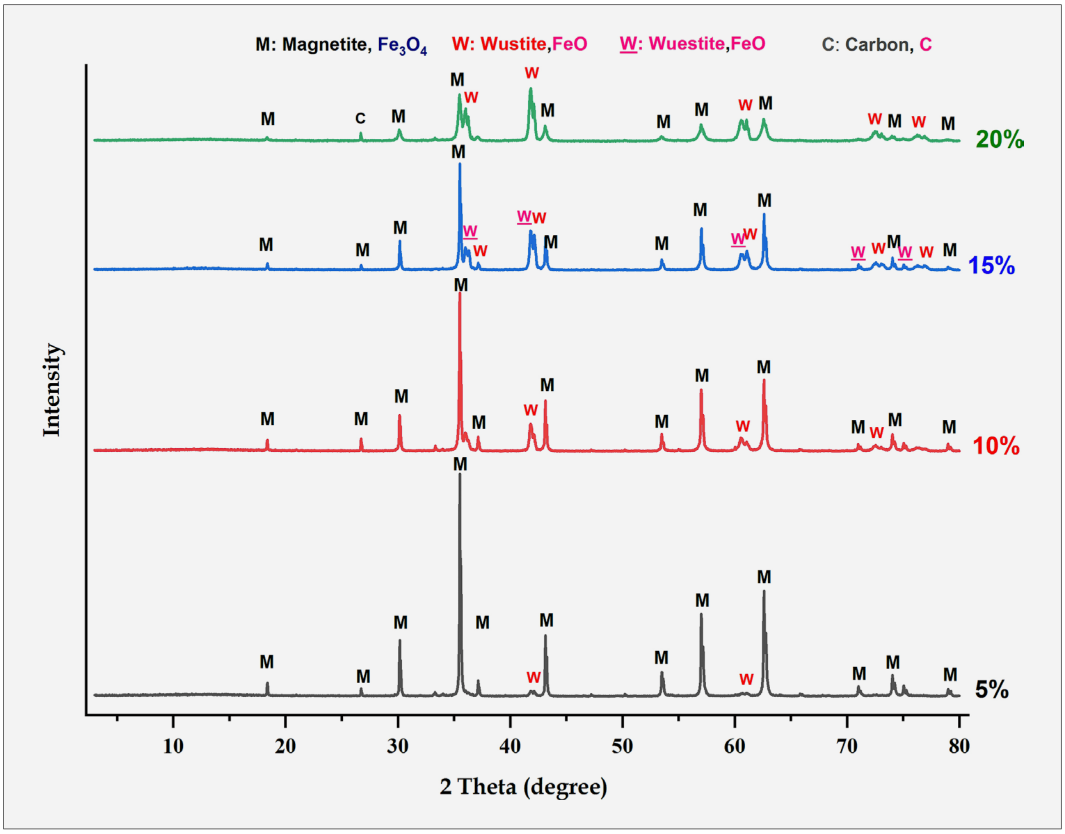

Figure 9: XRD patterns of reduced Um Nar BIF under different dosages of reductant

$$CaCO_3 = CaO + CO_2(g) \quad (3)$$

$$C(s) + CO_2(g) = 2CO(g) \quad (4)$$

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2 \quad (5)$$

$$Fe_3O_4 + CO = 3FeO + CO_2 \quad (6)$$

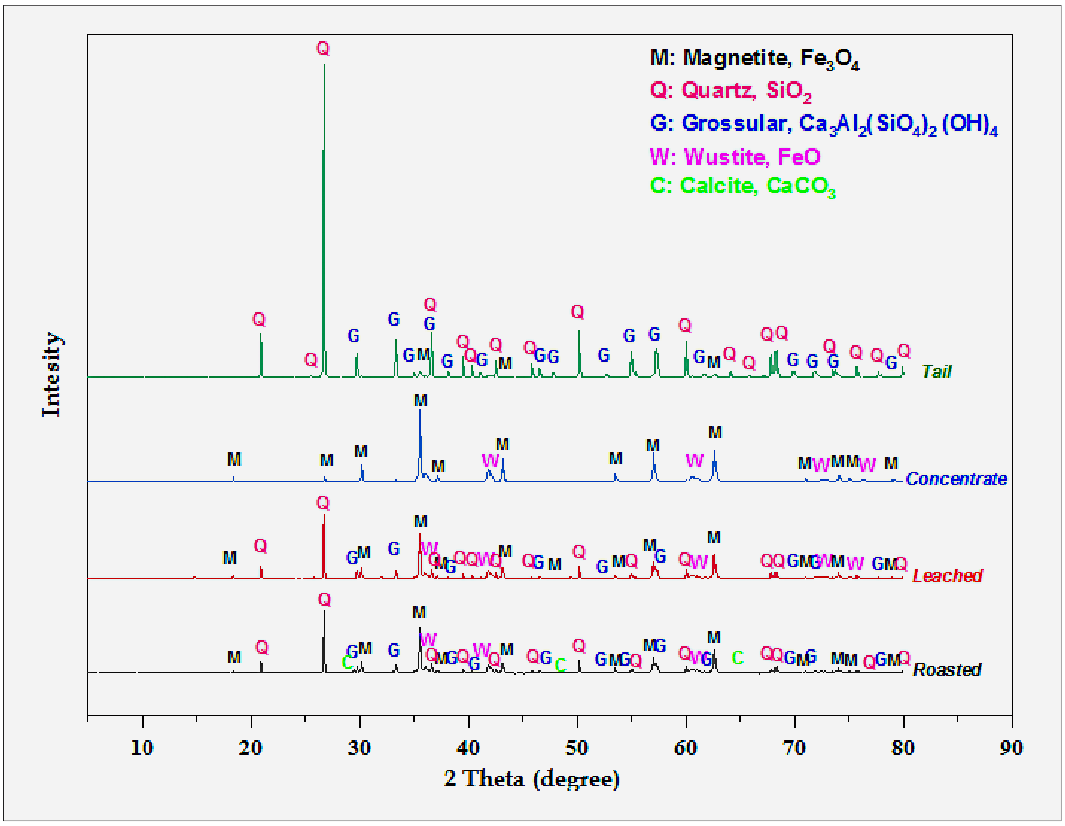

Figure 10: XRD patterns of roasted ore, leached ore, iron concentrate and tail in the presence of 10% dosage of reductant

The observed reduction in silica content with increasing reductant dosage highlights the effectiveness of this approach in managing silica impurities within iron ore processing. By preferentially reacting of $CaCO_3$ with Si and Al minerals, the formation of grossular ($Ca_3Al_2(SiO_4)_2(OH)_4$) plays a pivotal role in this process. This compound, being a stable and non-magnetic phase, effectively sequesters the silica, thereby preventing it from participating in unwanted reactions with iron oxides.

Furthermore, the XRD patterns presented in **Figure 10** corroborate these observations by displaying distinct peaks attributable to grossular in the roasted ore. The leached and tail products demonstrate significantly diminished peaks for SiO_2, indicating that silica is effectively sequestered within the grossular phase rather than persisting in the iron ore or being transferred into the leachate or tailings. This evidence clearly signifies that the process is functioning as designed to improve iron recovery and purity.

3.4. Effect of magnetic field intensity

Figure 11 illustrates the effect of varying magnetic field intensity on the reduced Um Nar BIF under optimal conditions using a mixture of $CaCO_3$ and sawdust at a content of 10%. The data reveal a significant impact of field intensity on the recovery and grade of total iron. As the magnetic field intensity increases from 700 to 2000 gauss, there is a modest rise in the total Fe grade, from 66.60% to 67.23%, accompanied by a notable improvement in total Fe recovery, from 63.17% to 73.82%. Concurrently, the silica content in the concentrate decreases from 2.44% to 1.54%. This trend can be attributed to the enhanced magnetic attraction of iron-bearing minerals at higher field intensities, which facilitates their more efficient separation from silica. Although silica is predominantly non-magnetic, some weakly magnetic silica particles may still be present in the concentrate, especially at lower field strengths. Enhancing the magnetic field intensity helps to minimize their presence in the concentrate (**Svoboda, 2004**).

Therefore, the magnetic field intensity of 2000 gauss was identified as the optimal intensity, which maximizes the total Fe grade and recovery while minimizing the silica content in the concentrate. Beyond this intensity, any further gains in recovery are expected to be minimal and may be outweighed by negative factors, such as decreased selectivity. Excessively strong magnetic fields may begin to capture non-magnetic or weakly magnetic impurities, reducing the effectiveness of separation (**Svoboda, 2004**).

3.5. Iron concentrate quality and its comparison with industry specifications and other research results

The XRD analysis (see **Figure 12**) reveals magnetite as the predominant mineral phase in the final concen-

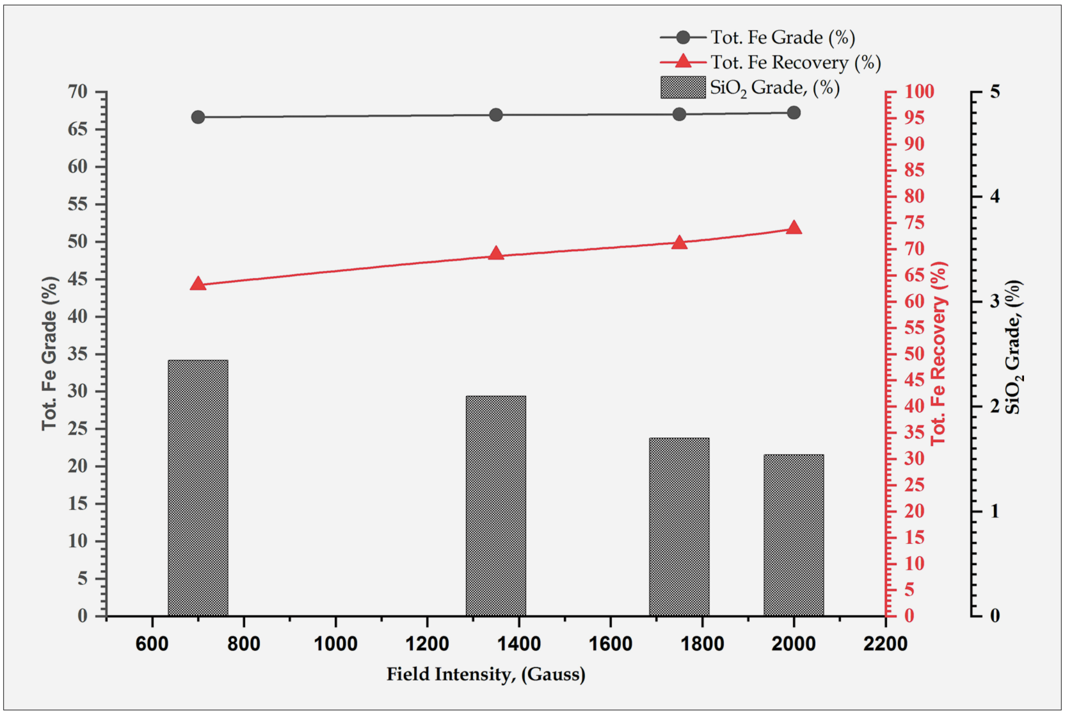

Figure 11: Effect of magnetic field intensity on the reduced Um Nar BIF

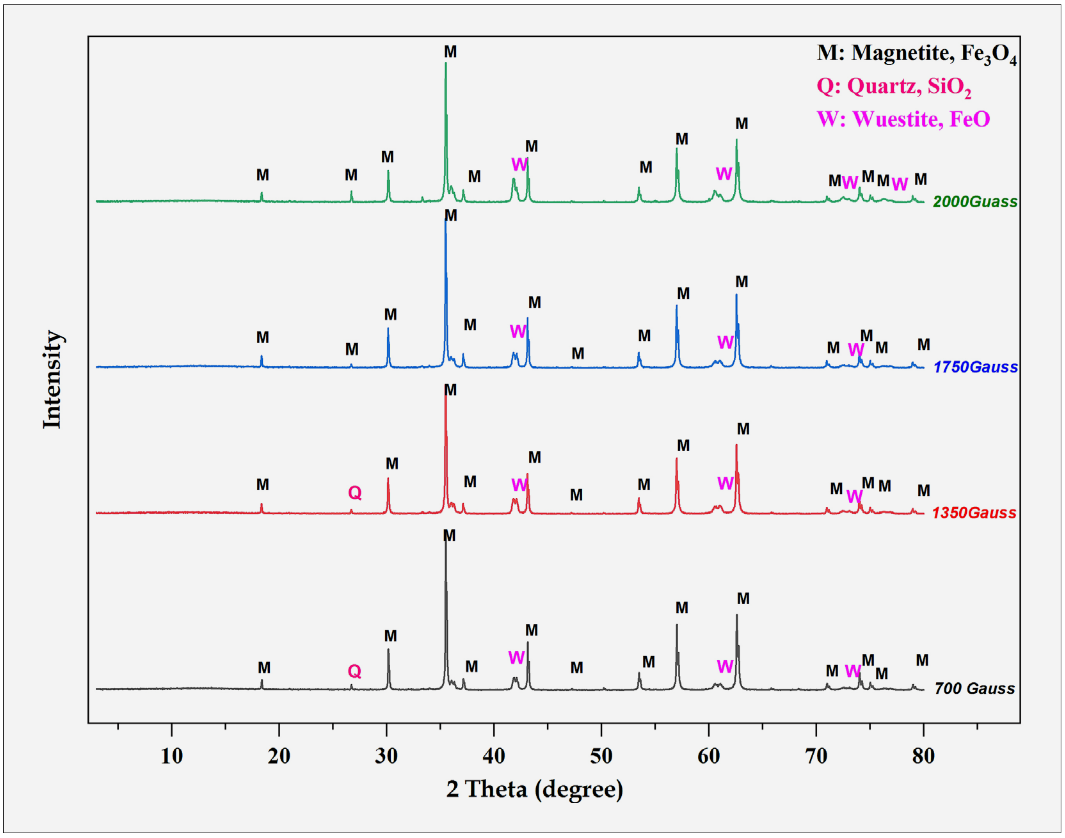

Figure 12: XRD patterns of reduced Um Nar BIF at different magnetic field intensity in the presence of 10% dosage of reductant

trates, with minor amounts of quartz and wustite. This confirms that the reduction roasting process was successful in converting the original iron oxides (hematite, goethite) to magnetite, which is more amenable to magnetic separation. The presence of wustite, a non-stoichiometric iron oxide, suggests that the reduction process

Table 6: XRF analysis of the concentrate

Constituents	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	Cl	P_2O_5	SO_3
Grade %	1.54	1.15	96.25	0.11	0.25	0.15	0.06	0.04	0.09	0.30	0.05

Table 7: Important global iron ore specifications (**S&P Global Platts, 2024**)

Iron ore type	Physical size (mm)	Specification (wt%)					
		Tot. Fe	SiO_2	Al_2O_3	P	S	Moisture
Lump (premium)	max 15% < 6.3 and max 15% > 31.5	62.5 min	3.5 max	1.5 max	0.075 max	0.05 max	4.0 max
Fines (premium)	< 6.3, max 10% up to 10.0	65.0 min	2.0 max	1.4 max	0.065 max	-	8.5 max
High-grade fines	< 6.3, max 10% up to 10.0	62.0 min	4.0 max	2.25 max	0.09 max	0.02 max	8.0 max
Low-grade fines	< 6.3, max 10% up to 10.0	58.0 min	6.0 max	2.9 max	0.06 max	-	8.0 max

may not have been complete for all iron oxides, but the overall conversion to magnetite was dominant.

The result of XRF analysis of the final concentrate, from the reduced Um Nar BIF treated with 10% of reductant during reduction roasting and magnetic separation at 2000 gauss, is displayed in **Table 6**. The results (see **Figure 11** and **Table 6**) show a magnetic separation concentrate with a total Fe grade of 67.23% (Fe_2O_3 = 96.25%), 73.82% total Fe recovery and a SiO_2 content of 1.54%, meeting premium lump and fines specifications (see **Table 7**). The concentrate also has acceptable levels of Al_2O_3 and SO_3, aligning well with industry standards for premium iron ore fines. However, the phosphorus content slightly exceeds the maximum allowed both for lump ore and fines. Overall, the concentrate of high iron content and low impurities make it suitable for industrial applications.

The SEM-EDS analysis (see **Figure 13**) of the final concentrate indicates that Fe and O are the main chemical components, confirming the predominance of magnetite (Fe_3O_4) in the concentrate. The prism structure observed in the SEM images suggests that the magnetite crystals are well-formed and likely contributed to the high iron recovery. In contrast, the EDS analysis of the raw ore (see **Figure 5**) shows a more uniform distribution of Fe, Si, Ca, and O. This suggests that the raw ore had a more complex mineralogical composition with iron particles closely associated with silica and other gangue minerals. The reduction roasting process facilitated the dissociation of iron particles from these gangue minerals, allowing them to aggregate and form a concentrate with higher iron content.

Table 8 provides a comparative analysis between the current study and other research conducted across different countries, utilizing various reducing agents. A comparison of the iron reduction results shows considerable differences in efficiency, which are influenced by factors such as ore type, geographical location, the reductant

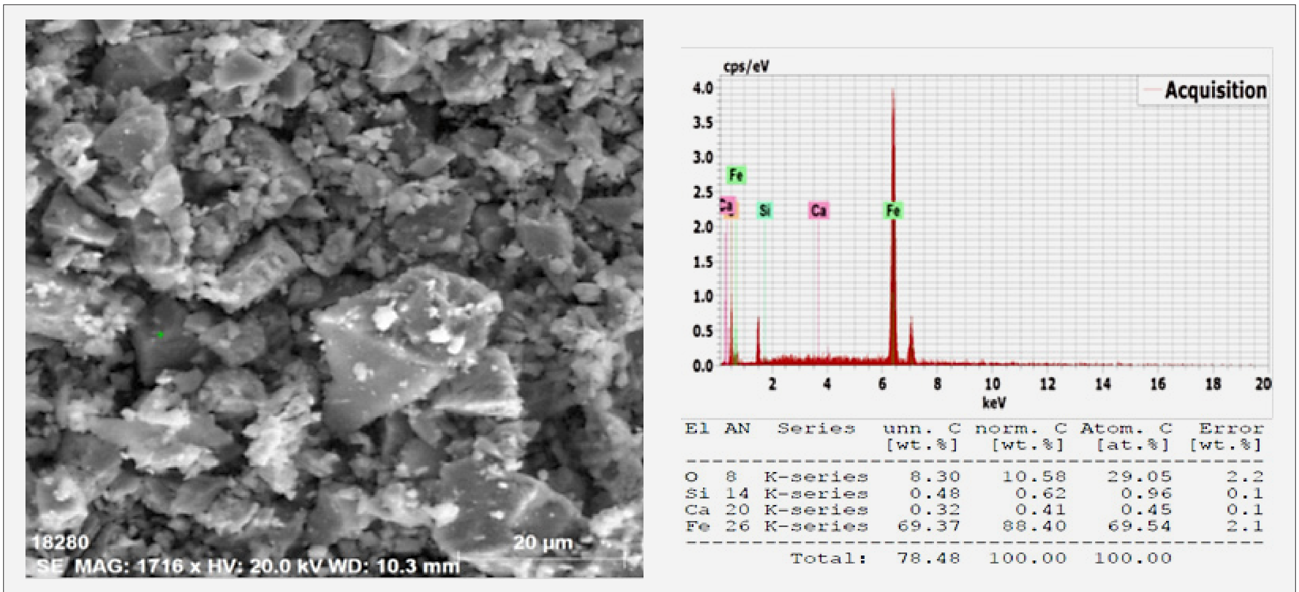

Figure 13: SEM-EDS results of reduced and separated Um Nar BIF with a 10% dosage of mixture of $CaCO_3$ and sawdust

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Table 8: Comparison between current study and other works

Ref.	Ore	Locality of sample "Country"	Reductant	Conditions	Results
Current study	BIF (45.10% Fe, 25% SiO_2)	Um Nar Eastern Desert, Egypt	Mixture of paper industry sludge and beech pine wood sawdust.	• The process consisted of three stages: reduction roasting with 10% paper industry sludge (as calcium carbonate) and sawdust, followed by acid leaching and magnetic separation at 2000 gauss.	• 67.23% tot. Fe grade, 73.82% Fe recovery and 1.54% SiO_2 grade
Zhang et al., (2023)	Hematite (67.22% Fe)	Anshan City, Liaoning Province, China	Waste corn straw	• At 700°C for 8 minutes, with a 1:4 corn straw to hematite ratio and a N_2 flow rate of 300 mL/min	• 69.82% iron grade and 93.95% iron recovery
Pan et al., (2022)	High-phosphorus oolitic hematite ore (HPOHO) (49.41% Fe, 14.52% SiO_2, 2.13% P_2O_5)	Guangxi Province, China	Bituminous coal was used as a reductant and analytical grade NaOH was used as an additive	• Sodium magnetization roasting at 1000 – 1100°C, followed by magnetic separation and acid-alkaline leaching.	• The final product assayed at 64.11% iron and 0.097% P_2O_5
Wu et al., (2019)	Iron ore (40.10% Fe, 9.40% Al, 6.92% Si and 8.69% Mn).	Yongzhou city, Hunan Province, China	$CaCO_3$	• Consisted of three stages: reduction roasting at 7% $CaCO_3$, acid leaching followed by magnetic separation.	• 53.73% Fe, 9.02% Mn, 7.51% Al and 2.46% Si, with 88.20% Fe recovery

used, and the specific conditions applied in each case. The results of the current study indicate that the mixture of paper industry sludge (as a source of calcium carbonate) and sawdust is an effective reducing agent for the Um Nar BIF, demonstrating its potential to efficiently recover high-quality iron. **Zhang et al. (2023)** studied hematite (67.22% Fe) from Anshan City, China, and found that using waste corn straw at 700°C for 8 minutes resulted in a 69.82% Fe grade and 93.95% Fe recovery. This highlights the high reactivity of hematite and the effectiveness of the reduction conditions. The study by **Pan et al. (2022)** on high-phosphorus oolitic hematite ore (HPOHO) from Guangxi Province, China, used bituminous coal as a reductant and analytical grade NaOH as an additive. The process involved sodium magnetization roasting at 1000–1100°C, followed by magnetic separation and acid-alkaline leaching, resulting in a final product assaying 64.11% iron and 0.097% P_2O_5. This method highlights the importance of process optimization, particularly in treating complex ores like high-phosphorus oolitic hematite. The study by **Wu et al. (2019)** focused on iron ore (Fe 40.10%, Al 9.40%, Si 6.92%, and Mn 8.69%) from Yongzhou City, Hunan Province, China. Calcium carbonate ($CaCO_3$) of analytical reagent grade was innovatively introduced into the roasting process at 7%. The roasted ore was then subjected to acid leaching followed by magnetic separation, resulting in a product containing 53.73% Fe, 9.02% Mn, 7.51% Al, and 2.46% Si, with an Fe recovery rate of 88.20%. Overall, these studies highlight the critical role of ore type, reductant choice, and reduction conditions in determining the efficiency and outcomes of the iron reduction process.

4. Conclusions

This study demonstrated that utilizing paper industry waste (specifically calcium carbonate) and sawdust in the direct reduction process, followed by acid leaching and magnetic separation, is an effective method for processing Um Nar BIF. The final stage of magnetic separation efficiently recovered iron-rich concentrate that meets the quality standards for steel production. Adding calcium carbonate ($CaCO_3$) resulted in its preferential reaction with Si and Al minerals to form grossular. This prevented SiO_2 from reacting with iron oxides, thereby promoting iron recovery. This innovative approach not only enhanced the efficiency of iron ore processing but also provided a sustainable solution for recycling industrial waste, contributing to environmental conservation and resource management. The successful application of this method in industry could lead to significant advancements in both waste management and mineral processing, especially for complex and low-grade iron ores. The iron concentrate obtained through this technology, i.e. reduction roasting conducted with 10% dosage of reductant, followed by acid leaching and magnetic separation at 2000 gauss, contains 67.23% total iron (Fe) and only 1.5% silicon dioxide (SiO_2), with a total iron recovery of 73.82%, meeting the quality requirements of the steel and iron industry.

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SAŽETAK

Poboljšanje odvajanja i iskorištenja željeza iz rude egipatskih uslojenih formacija željeza pomoću mulja iz industrije papira: održivi pristup redukcijskom prženju

U članku se predlaže inovativna metoda za poboljšanje koncentrata dobivenoga iz rude uslojenih željeznih formacija Um Nar (Banded Iron Formation – BIF). Metoda se sastoji od triju faza: redukcijskoga prženja korištenjem mulja iz industrije papira i piljevine, luženja sumpornom kiselinom i magnetske separacije. Ispitivani su učinci koncentracije smjese $CaCO_3$ i piljevine te intenziteta magnetskoga polja. Ovaj pristup ne samo da pruža učinkovit način prerade složenih i niskokvalitetnih željeznih ruda, već nudi i održivo rješenje za recikliranje industrijskoga otpada. Osim toga, koristi se piljevina biomase kao zeleni redukcijski agens, nova vrsta čistoga izvora energije s niskim udjelom sumpora, koji ne zagađuje okoliš. Dodavanje kalcijeva karbonata ($CaCO_3$) u obliku mulja papirne industrije dovelo je do njegove reakcije s mineralima silicija i aluminija stvarajući grosular ($Ca_3Al_2(SiO_4)_2(OH)_4$). To je spriječilo reakciju SiO_2 s oksidima željeza, čime se povećalo iskorištenje željeza. Dobiveni koncentrat željeza zadovoljava standarde kvalitete potrebne za proizvodnju čelika. Koncentrat željeza dobiven ovom metodom, tj. redukcijskim prženjem provedenim s 10%-tnom dozom reducensa, ispiranjem kiselinom i magnetskom separacijom pri 2000 gausa, sadržava 67,23 % željeza i 1,5 % SiO_2 s ukupnim iskorištenjem željeza od 73,82 %, što zadovoljava zahtjeve industrije čelika i željeza za kvalitetu željezne rude.

Ključne riječi:
Um Nar, BIF, redukcijsko prženje, biomasa – piljevina, kalcijev karbonat, mulj industrije papira

Author's contribution

Mostafa A. Metwally (Assistant Lecturer, Faculty of Engineering, Al-Azhar University) gathered samples (BIF, biomass-sawdust and paper industry sludge), characterized the samples, and contributed to the crushing, grinding, reduction roasting, acid leaching and magnetic separation processes. **El-Sayed R. E. Hassan** (Associate Professor of Mineral Processing at CMRDI) also contributed to the crushing, grinding, reduction roasting, acid leaching and magnetic separation processes, and described the characterization and evaluation of the final products. **A. M. Ramadan** (Professor of Mineral Processing, Faculty of Engineering, Al-Azhar University) and **Mohamed G. Farghaly** (Professor of Ore Dressing, Faculty of Engineering, Al-Azhar University) evaluated the results, reviewed the draft manuscript, and provided technical suggestions. The entire work was written collaboratively by all the authors.