RGNZ/MGPB

Beneficiation of Ferruginous Manganese Ore of Um Bogma Locality, Sinai: Comparison Between Conventional Reduction Roasting Techniques and Microwave Technology

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 6: 66: 66.08: 667.6
DOI: 10.17794/rgn.2024.5.6

Original scientific paper

Ahmed Moustafa[1*], Nagui Abdel-Khalek[2], Ahmed Sharaf-Eldin[1], Abdelmonem Soltan[1], El-Sayed Hassan[2]

[1] Geology Department, Faculty of Science, Ain Shams University, Abbassia, 11566, Cairo, Egypt

[2] Minerals Beneficiation and Agglomeration Department, Minerals Technology Division, Central Metallurgical Research & Development Institute (CMRDI), P.O. Box 87 Helwan, 11722 Cairo, Egypt

Abstract

The increasing demand for high-grade manganese ores in various industries has led to a growing necessity to enhance the quality of lower-grade manganese ores with time. A representative manganese ore was collected from Um Bogma, Sinai, Egypt, and subjected to various characterization methods including X-ray diffraction (XRD), X-ray fluorescence (XRF) and ore microscopy. XRF analysis revealed a low Mn/Fe ratio of 2.81 (as elements), indicating a low ore grade. For suitability in Mn alloy production at the Sinai Manganese Company (SMC) plant in Abu Zenimah, southeast of Sinai, Egypt, this ratio should ideally exceed 5. Additionally, XRD and ore microscopy identified the mineralogical composition of the ore as pyrolusite, hematite, and manganite, with manganese patches embedded in a ferruginous groundmass at the textural scale. Three different reduction roasting techniques were evaluated, involving conventional heating in a furnace utilizing either $CO - CO_2$ or charcoal as reducing agents, alongside reduction roasting with charcoal utilizing microwave technology. Following each technique, magnetic separation was employed, resulting in the production of high-grade manganese concentrates exhibiting high Mn/Fe ratios ranging from 19.8 to 27.45 and substantial Mn recovery rates ranging from 93.86% to 96.76%.

Keywords:
manganese ore; Um Bogma; beneficiation; microwave heating; reduction roasting

1. Introduction

Manganese ore has an essential role in many industrial applications, especially in ferro-manganese and silico-manganese alloy manufacturing, which are very important in steel production, which needs at least Mn > 30% and a Mn/Fe ratio = 5 (**Tan et al, 2004**). In addition, manganese is applied in dry-cell batteries and other chemical industries worldwide (**Fahim et al., 2013; Yi et al., 2017; Liu et al., 2019; Gao et al., 2020**). The manganese is essentially extracted from manganese oxide and manganese carbonate ores (**Lei et al., 2021**). According to the USGS report (**USGS, 2023**), the leading country in exporting manganese ores was: Gabon with 67%; participation. Australia is ranked as the first country to export ferromanganese alloys with 19% participation. However, Georgia has the top participation with 28% to produce and export silicomanganese alloys. The beneficiation of manganese ores became, in the last decades, an essential preliminary step prior to their use in industrial applications. This is due to the high consumption rate of higher grades of manganese ores in many locations in the world (**Wan et al., 2021; Singh et al., 2020; Sinha et al., 2020**). Um Bogma Mn ore needs to be processed to meet the demand of the manganese consumptions in Egypt, **Figure 1** (**El-Shafei et al., 2022**). Many worldwide research studies were conducted on the beneficiation of low-grade manganese ores. The beneficiation methods mainly depend on the impurities of the ore and the needed industrial application (**Singh et al., 2020**). Regarding ferruginous manganese ores, it is quite hard to separate Mn and Fe because of the similarity in mineralogical characteristics (**Singh et al., 2021**).

The beneficiation tests based on comminution, magnetic separation, gravity, and flotation techniques did not reach the needed specifications for the manganese concentrates required for industrial demands (**Liu et al., 2019**). The chemical leaching and chemical treatments of the ferruginous manganese ore is a better way (**Tang et al., 2014; Zhang et al., 2015; Dan et al., 2016; Wang et al., 2017; Astuti et al., 2019**) but is not economically recommended, especially when it is applied on the industrial scale, because of the high cost. The reduction roasting treatment is a very good choice to upgrade ferruginous manganese ores, because it gives direct way to separate manganese from its associated iron compo-

Corresponding author: Ahmed Gamal Moustafa
e-mail address: ahmedgamal@sci.asu.edu.eg

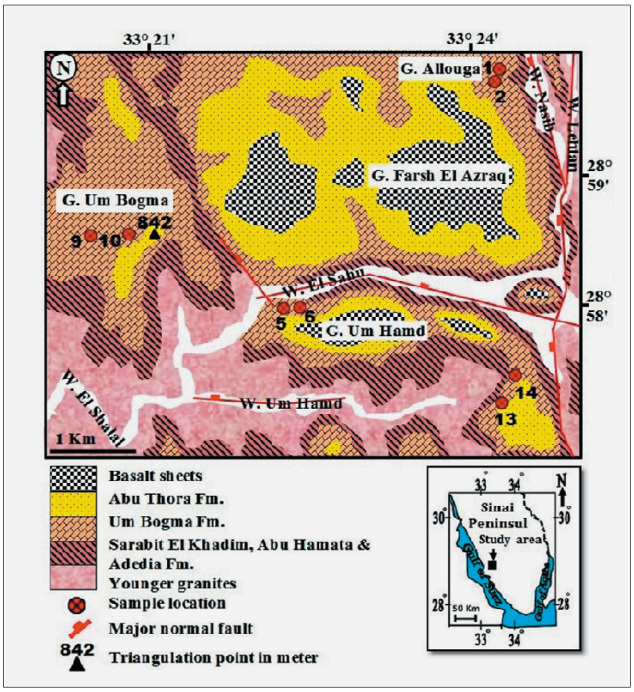

Figure 1: Geological map of Um Bogma area (**Sallam, 2018**)

nents, however it needs to be commercialized to be feasible for the beneficiation of the Mn ore (**Singh et al., 2021**). Many reducing agents were used in previous literature such as CO/CO_2 (**El-Geassy et al., 2000; Gao et al., 2012; Mpho et al., 2013; Yi et al., 2017; Larssen et al., 2021**), charcoal (**Zhang et al., 2015; Rath et al., 2018**), coke (**El-Hussiny et al., 2016; Singh et al., 2020**), and anthracite (**Yi et al., 2017**). The application of microwave technology, as a green, cheap, and fast alternative way to the conventional electrical heating techniques, recently attracted many researchers who work in the ore dressing field (**Amankwah & Pickles, 2005; Omran et al., 2014; Zhao et al., 2014; Elmahdy, et al., 2015; Omran, Fabritius, & Mattila, 2015; Celikdemir et al., 2016; Chen et al., 2017; Omran, Fabritius, Yoshikawa, 2018; Li et al., 2020; Lin et al., 2021; Zhou et al., 2021; Zhou et al, 2022**).

Several Um Bogma manganese ore samples were studied using several characterization techniques (**Moustafa et al., 2024**). The obtained results assessed their potentiality for processing. The detailed investigation of Um Bogma manganese ore samples revealed that: sample (1) was unsuitable for upgrading due to its low manganese content and mineral interlocking, while sample (4) was similarly unviable because of its primary manganite content. Conversely, samples (2) and (3) showed promise, with sample (3) being particularly amenable to mineral processing due to its favourable textural characteristics and mineral associations. The present study underscores the importance of tailored beneficiation strategies to enhance the Mn/Fe ratio for sample 3, focusing on comparing conventional and microwave reduction roasting treatments for enhanced manganese recovery. In addition, to compare, at optimal conditions, between conventional reduction roasting treatments and that of microwave reduction roasting treatment. The different reduced Mn samples will be subjected to magnetic separation to separate the magnetic fraction (mainly magnetite) from the non-magnetic manganese concentrates.

2. Materials and methods

A representative 30 kg run of mine (ROM) manganese ore sample is collected from Um-Bogma locality, Sinai, Egypt, which belongs to Sinai Manganese Company (SMC) mines. In addition, a sample of charcoal (as a reducing agent) is supplied by a private company. It assayed as 84.31% fixed carbon, 8.93% volatile matter and 6.76% ash content.

2.1. Sample comminution and screening

A laboratory Jaw crusher (5x6 Denver) was used for primary crushing of the ROM manganese ore sample. This was followed by a secondary crushing step using a (Wedag) roll crusher. Sieve analysis was performed for the secondary crushed ore using sieves 590, 250, 125, 75, and 53 µm mesh sizes. The crushed ore was directed to a grinding step in a closed circuit of screen (250 µm) to yield a ground product (100%) beneath the estimated liberation size (lower than 250 µm). This represents the feed to beneficiation experiments.

2.2. Sample characterization

The chemical analysis, of the ROM and concentrate samples, was performed using PANalytical Axios XRF spectrometer, Technical Institute, George Simon Ohm, Germany. A representative powder sample of 8 g was mixed with 2 g of Licowax C Micro-powder PM, then the mix was pressed to produce a disc that was inserted into the XRF machine to be measured. The XRF data errors of major and minor oxides in Um Bogma manganese ore samples are ±0.10% and ±0.01% respectively. The identification of the mineralogical phases (ROM and Mn samples) was carried out using Panalytical X'Pert PRO XRD device, Technical Institute, George Simon Ohm, Germany. About 2 g of each powder sample was pressed and measured as disc in the XRD machine with Cu-radiation (l = 1.542 Å) within a 2q range between 2q = 5°and 80°. The results were interpreted using PC "Match" software to calculate the semi-quantitative percentages of the presented mineral phases. The XRD data errors of Um Bogma manganese ore samples are ranged from ±0.10% to ±0.5%. A rock-cutting machine was used to get a hand specimen of the manganese ore sample, and then the specimen was mounted and polished. Then, the mounted polished sample was subjected to reflected-light microscope (Olympus. Portugal), with an attached camera and PC Olympus work-

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 89-100, DOI: 10.17794/rgn.2024.5.6

space software to take images and study the mineralogical and textural characteristics of the samples.

2.3. Liberation size assessment

In the beneficiation of low-grade ores, it is very important to determine the best liberation size that produces a higher degree of liberation between manganese minerals and their associated gangue constituents. This was achieved through the microscopic-textural examination of the ROM manganese ore sample. A screen size analysis was performed to support the estimation of liberation size, as a representative one-kilogram sample of the crushed manganese ore sample (30 kg) was sieved using various sieve mesh sizes (590, 250, 125, and 75 µm). Then, each size fraction was subjected to chemical analysis to estimate the best size fraction of maximum liberation.

2.4. Reduction roasting techniques

The conventional reduction roasting treatment of the manganese ore sample was carried out using two different reducing agents during reduction processes. The first one is a gas system (CO/CO_2) and the second one is a solid system (charcoal). The reduction using gas system CO/CO_2 was conducted using a prepared representative manganese ore sample of about 120 g. The sample is sieved beneath 250 µm, then adjusted in a horizontal tube electrical furnace with the optimal conditions of temperature = 700°C and (100-CO / (CO-CO_2)) gaseous condition ratio = 20 for 2.0 hr (**El-Geassy et al., 2000**). Then, the product was subjected to low-intensity magnetic separation to separate the magnetite phase from the manganese minerals. The second technique for reduction roasting was to use charcoal as a reducing agent (**Sharma, 1992**). This was performed using 'Nabertherm' electrical chamber-muffle, with the optimal conditions of a mix of -250 µm sized-sample of manganese ore (80 wt.%) and charcoal (20 wt.%). The mixture was subjected to thermal treatment at temperature 800°C for 2.0 hr. In recent years, the application of microwave muffle, as a novel technology, for thermal treatment of difficult to treat ores was studied to upgrade iron ores (**Omran, 2014**). So, it was decided to test this recent technology for thermal reduction of Um Bogma manganese ore. The experiment was performed using a «Sirem» microwave muffle at a power of 1.5 kW. The feed to microwave muffle was composed of a blend containing manganese ore (80 wt.%) of below 250 µm in size and charcoal (20 wt.%). The experiment was performed at a temperature of 800°C for 0.13 hr.

2.5. Magnetic separation of different reduced samples

Application of wet magnetic separation, after reduction roasting, for different samples was established using a 'Davis tube' wet magnetic separator device. This process aimed to separate the paramagnetic (non-magnetic) fraction, that would not be attracted to the low intensity magnet, that represented the manganese concentrate fraction, from the ferro-magnetic (magnetic) fraction represented by the iron bearing mineral phase "magnetite Fe_3O_4". The optimal conditions were established (**Ahmed, 1977; Galal, 2002**), as 20 g of the treated sample was subjected to a magnetic field of 300 gauss, a tube axis inclination equal to 220° from horizontal, a wash water rate of 400 cm^3/min for 0.25 hr, and an oscillation rate equal to 64 cycle/min.

3. Results and discussion

3.1. Characterization of Um Bogma manganese sample

Table 1 shows the results of the X-ray fluorescence analysis (XRF) of the ROM sample. In the context of Um Bogma manganese ore, XRF analysis could provide valuable information on the concentrations of not only manganese but also other elements that may be present as impurities. Common elements of interest in manganese ore analysis include iron, silicon, aluminium, calcium, magnesium. The major oxides are MnO (55.40%) and Fe_2O_3 (21.86%). This means that the Mn/Fe ratio of 2.81 (as elements) is low. This ratio should be greater than 6 to be suitable for Mn alloys production. Also, SiO_2 (2.52%) and CaO (1.98%) represent minor oxides exceeding 1%. Other minor oxides (such as Al_2O_3, MgO, P_2O_5, SO_3, K_2O, CuO, ZnO, and BaO) vary between 0.38 and 0.67%. The values of oxides (such as Na_2O, Cl, NiO, and SrO) are trace amounts. In addition, the loss-on-ignition (LOI) is about 12%.

According to the mineralogical study of the manganese ore sample (see **Figure 2**), the XRD diffraction patterns show that pyrolusite (MnO_2) (85.9 wt.%, PDF No.

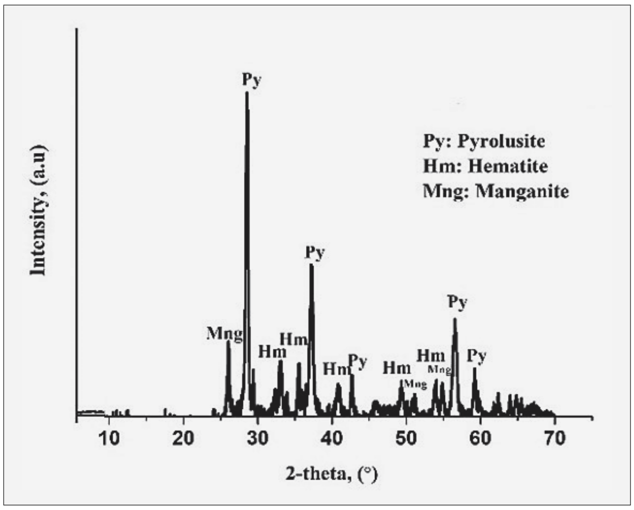

Figure 2: X-ray diffraction pattern of Um Bogma Manganese ore. (Py: pyrolusite, Hm: Hematite, Mng: Manganite)

Table 1: X-ray fluorescence results for Um Bogma manganese ore sample and the different ore size fractions

Oxide (%)	Um Bogma manganese ore sample (ROM)	-590 +250 µm	-250 +125 µm	-125 +75 µm	-75 +53 µm
Na_2O	0.16	0.18	0.20	0.15	0.18
MgO	0.47	0.88	0.93	0.97	0.95
Al_2O_3	0.67	1.10	1.14	1.22	1.57
SiO_2	2.52	2.69	2.93	3.22	3.88
P_2O_5	0.52	0.61	0.36	0.32	0.27
SO_3	0.38	0.42	0.43	0.45	0.51
Cl	0.11	0.04	0.03	0.03	0.04
K_2O	0.35	0.69	0.77	0.72	0.67
CaO	1.98	1.30	1.21	1.27	1.37
TiO_2	0.02	--	--	--	0.05
Cr_2O_3	0.02	0.03	0.03	0.03	--
MnO	55.40	55.45	56.31	55.54	54.42
Fe_2O_3	21.86	21.98	21.66	21.64	21.52
NiO	0.04	0.05	0.05	0.05	0.06
CuO	0.47	0.11	0.09	0.09	0.11
ZnO	0.64	0.47	0.50	0.45	0.45
As_2O_3	0.03	0.04	--	--	0.05
SrO	0.19	0.11	0.11	0.11	0.10
Y_2O_3	0.02	0.02	0.02	0.02	0.02
BaO	0.52	1.26	1.15	1.21	1.10
PbO	0.04	0.04	0.04	0.06	0.03
LOI	12.25	12.56	12.04	12.43	12.70

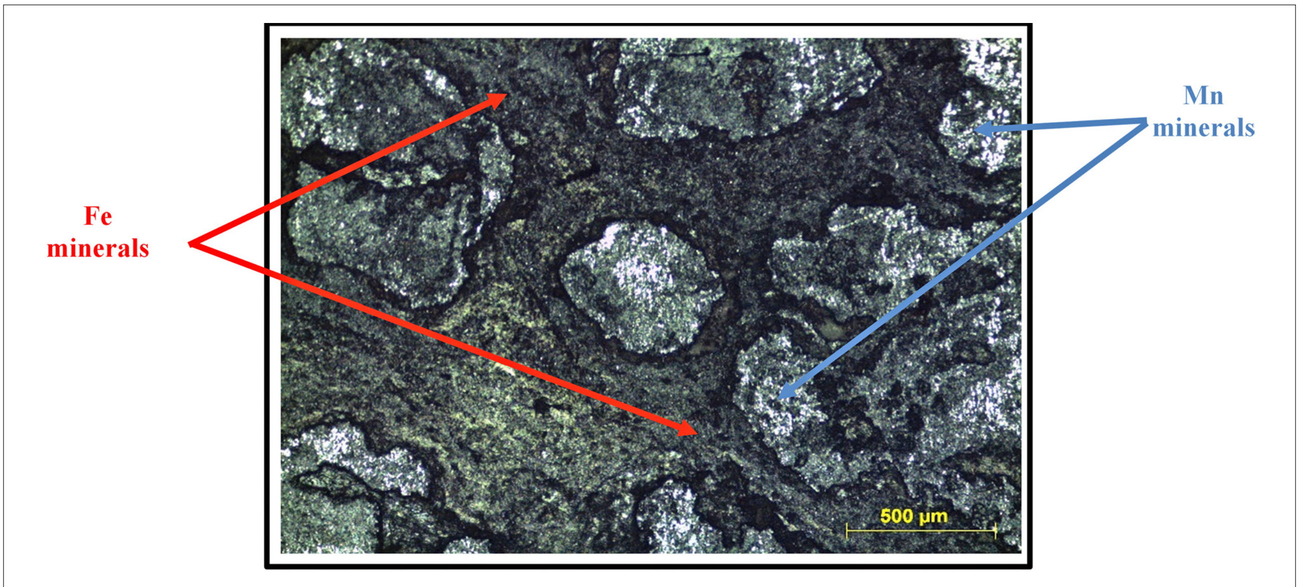

Figure 3: Photomicrograph of polished section of Um Bogma manganese ore sample under reflected light microscopy

96-900-9083) represents the major Mn mineral phase, in addition to hematite (Fe_2O_3) (10 wt.%, PDF No. 96-900-0140) with the low existence of manganite (MnO(OH)) (4.1 wt.%, PDF No. 96-901-6547). Pyrolusite and hematite minerals are paramagnetic and therefore direct magnetic separation is not convenient for efficient separation of these minerals from each other. A reduction roasting process would convert hematite into magnetite and consequently the separation of paramagnetic pyrolusite from the ferromagnetic magnetite could be achieved with a Davis tube as a low intensity magnetic separator.

The reflected-light ore microscopy examination (see **Figure 3**) shows that the manganese ore is composed mainly of light-coloured phases, which represent manganese minerals (pyrolusite MnO_2 and manganite MnO(OH)). On the other hand, the darker phases represent iron bearing mineral (hematite Fe_2O_3). The texture displays semi-equant polygonal particles of manganese minerals immersed in the ferruginous groundmass.

3.2. Liberation size assessment

Based on the microscopical study of the manganese ore's polished section (see **Figure 4a, b and c**), it is clear that the predominant texture observed in the manganese ore sample is granular manganese patches, distinguishable by their (yellowish white) appearance, dispersed within a groundmass primarily composed of iron mineral phases with (faint and dark brown). This granular texture suggests a heterogeneous distribution of manganese within the ore matrix, indicating that liberation processes may be necessary to extract the manganese content efficiently. The described textural pattern implies that the manganese granules are encapsulated within the surrounding iron mineral phases, potentially hindering their liberation during subsequent processing stages. Liberation, in this context, refers to the process of breaking down the ore particles to release valuable minerals from their host matrix, thereby making them accessible for further beneficiation. The estimation of the average radius of the manganese granules, believed to be below 250 µm, is crucial for determining the optimal size range for comminution processes. Comminution involves crushing and grinding operations aimed at reducing the particle size of the ore to facilitate the liberation of valuable minerals. The identified liberation size provides a target for the comminution circuit, guiding the selection of appropriate crushing and grinding equipment to achieve efficient liberation of manganese from the ore matrix. Achieving liberation sizes below the estimated average radius of the manganese granules is essential to maximize the recovery of manganese and optimize the overall processing efficiency. However, it is important to note that liberation size assessment is influenced by various factors, including ore mineralogy, texture, and the desired end product specifications.

Figure 5 presented the size and cumulative analysis of the studied manganese ore sample. Most of the weight (about 81 wt.%) of sample lie between -125 µm +75 µm in size. About 90% by weight (d_{90}) lies in sizes less than about 400 µm while the d_{50} of the sample at about 125 µm. These results depict that a such ground sample has a reasonable degree of liberation. In general, the existence of a high percentage of iron in Um Bogma manganese ore is expected, as it is a ferruginous ore type (**Kordi et al., 2017; Araffa et al., 2020; and El-Shafei et al., 2022**). The concentrations of Fe_2O_3 are in the reverse order which was explained by **Fahim et al. (2013)**.

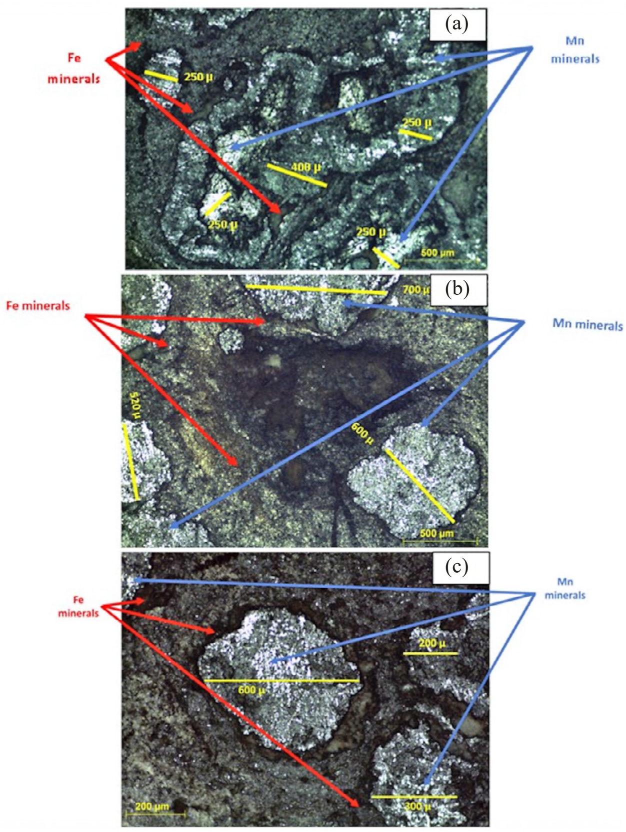

Figure 4: The photomicrographs show the estimation of manganese grains liberation size (average 250µ) through textural examination of manganese ore sample polished section (a) in the range 250-400 µm (b) in the range 520-700 µm (c) in the range 200-600 µm.

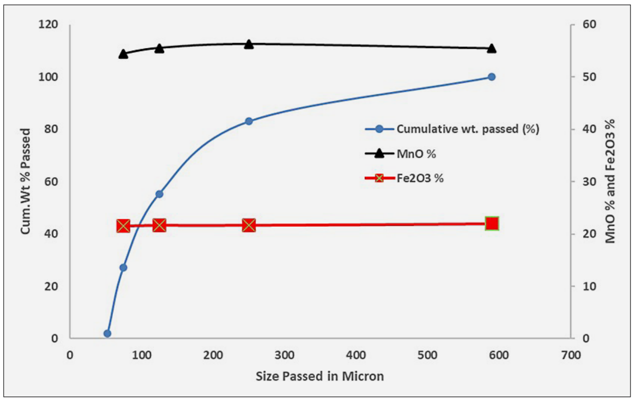

Figure 5: Distribution of MnO and Fe_2O_3 in different size fractions of manganese sample

The XRF analysis of different size fractions are illustrated (see **Table 1**). The results highlight the distribution of various oxides across different particle sizes. Manganese oxide content is highest in the -250 +125 µm fraction (56.31%) and lowest in the finest fraction (54.42%). This shows manganese concentration slightly decreases with finer particles but remains relatively high across all sizes, indicating that Um Bogma manganese ore has a consistently high MnO content. Iron oxide content remains relatively stable across all fractions, indi-

 pp. 89-100, DOI: 10.17794/rgn.2024.5.6

Table 2: X-ray fluorescence of different manganese concentrates in comparison to ROM samples

Oxide %	ROM	Conv + CO/CO_2	Conv + charcoal	Microwave + charcoal
MnO	55.40	82.18	89.04	89.26
Fe_2O_3	21.86	3.32	3.84	4.99
MgO	0.47	0.53	0.53	0.59
CaO	1.98	0.85	1.26	1.48
Al_2O_3	0.67	1.13	0.90	0.91
SiO_2	2.52	1.74	0.99	1.35
SO_3	0.38	2.77	0.09	0.13
Cl	0.11	0.02	0.00	0.00
K_2O	0.35	0.21	0.26	0.17
NiO	0.04	0.00	0.04	0.03
CuO	0.47	0.1	0.06	0.06
ZnO	0.64	0.21	0.61	0.13
% as Metal				
Mn%	42.95	63.6	68.92	69.08
Fe%	15.29	2.32	2.68	3.49
Mn/Fe	2.81	27.45	25.71	19.82
Recovery%	-	93.89	96.43	96.76

cating an even distribution of iron oxide in the ore. These results supported the estimated liberation size where the values of MnO (54.42 – 56.3%) and Fe_2O_3 % (21.52 -21.98%) are, more or less, evenly distributed in different size fractions (see **Figure 5**). The variations in other oxides, particularly SiO_2, Al_2O_3, and P_2O_5, suggest differential distribution of these elements, which could impact the ore beneficiation and processing. The presence of high SiO_2 and Al_2O_3 in finer fractions might require additional treatment steps to achieve optimal manganese extraction. Titanium, chromium, arsenic, yttrium, strontium and lead oxides, along with chlorine are present in very low concentrations across all fractions.

3.3. Results of reduction roasting followed by magnetic separation

Beneficiation of ferruginous manganese ores by physical methods, such as gravity separation or direct application of magnetic separation techniques, did not give satisfactory results (**Sharma, 1992; Youssef & Abdel-Khalek, 2011**). This is due to the similarities between manganese and its associated iron bearing minerals. For this reason, the best way to beneficiate such ferruginous manganese ore is to conduct a reduction roasting process under certain conditions. This leads to transforming iron oxides (mainly hematite, Fe_2O_3) into the magnetite (Fe_3O_4) phase. It is known that magnetite has high magnetic susceptibility followed by hematite and goethite (**Ravisankar et. al., 2017**). Hence, magnetite, as a ferromagnetic mineral, can be easily attracted to a low-intensity magnetic field while manganese oxides will be separated as non-magnetic (**Sharma, 1992**).

Proper reducing agents such as carbon (e.g. charcoal) and CO gas are conducted during this study as reducing agents for hematite to be converted into magnetite at a specific temperature and duration of reduction. Any iron oxide can undergo reduction through carbon monoxide in three distinct stages above 570°C (**Chartterjee, 2010**):

Stage: Stage 1 → Stage 2 → Stage 3

Phase: Fe_2O_3 → Fe_3O_4 → Fe

This reduction roasting or magnetizing roasting process transforms a particle or substance from having non-weak magnetic properties to exhibiting high magnetic content within a critical temperature range of 500 to 900°C, employing a reducing agent over a specific time frame. Below this critical temperature, the conversion and reduction processes remain incomplete, while above it, fusion leads to the formation of wustite, a paramagnetic material. The particle transformation is described by the equations provided below (**Jang et al., 2014**).

$$2\,FeO(OH) \rightarrow Fe_2O_3 + H_2O \quad (1)$$

$$3\,Fe_2O_3 + CO \rightarrow 2\,Fe_3O_4 + CO_2 \quad (2)$$

$$Fe_3O_4 + CO \rightarrow 3\,FeO + CO_2 \quad (3)$$

The reduction of iron oxide occurs through the CO mechanism, as illustrated in Boudouard diagram (**Jang et al., 2014; Dawei et al., 2014**). The Boudouard diagram displays that below the temperature range of 600-800°C, and CO/CO_2 gaseous environment of [100*CO/(CO*CO_2)] equals a value in the range of 5-30, (see **Figure 8**) the iron bearing minerals including hematite would be converted into a magnetite phase (**Jang et al., 2014; Dawei et al., 2014**).

Charcoal, serving as a solid carbon source, is also employed as a substitute for CO/CO_2 gas systems. In such

 pp. 89-100, DOI: 10.17794/rgn.2024.5.6

instances, the reduction roasting process advances in two phases. Initially, carbon undergoes transformation into CO gas at elevated temperatures, wherein carbon atoms combine with oxygen atoms to yield CO_2 and CO gases. This initial phase sets the stage for reduction in the subsequent step for hematite (**Sharma, 1992**), depicted as:

$$2\,C + O_2 \rightarrow CO_2 \quad (4)$$

$$CO_2 + C \rightarrow 2\,CO \quad (5)$$

Reduction roasting process for manganese samples has been conducted by three different techniques as follows:

1 – Reduction roasting in a muffle furnace using a (CO/CO_2) gas system as a reducing agent,

2 – Reduction roasting in a muffle furnace using charcoal as a solid reducing agent, and

3 – Reduction roasting using a microwave muffle in the presence of charcoal as a solid reducing agent.

The reduction roasting processes are carefully controlled in such a way that the associated 'hematite' phase will be reduced to a 'magnetite' phase which can be easily attracted to a magnetic separator. The reduced samples, produced from the application of such different reduction roasting techniques, are subjected to a magnetic separation process using a 'Davis Tube' magnetic separator unit. The latter separates the reduced samples into two fractions. A magnetic (magnetite Fe_3O_4) fraction from the non-magnetic (manganese) product. The different non-magnetic products (manganese concentrates) are subjected to evaluation using XRF and mineralogical (XRD) analyses as shown below.

3.3.1. X-ray fluorescence (XRF) analysis of manganese concentrates

The non-magnetic products (manganese concentrates) are subjected to XRF analysis, the results of which are shown in **Table 2**. These results for Mn concentrates are compared with that of a ROM sample. The content of MnO% is increased significantly in the three Mn concentrates. For example, MnO% is increased from 55.40% in ROM to about 82.18% MnO in non-magnetic concentrate as a result of reduction roasting in a furnace equipped with a CO - CO_2 gas system as a reducing agent. Also, MnO% is increased to about 89.04% in the non-magnetic concentrates after reduction roasting in a muffle furnace using charcoal as a reducing agent. On the other hand, the application of the reduction process in a microwave in the presence of charcoal as a reducing agent, followed by magnetic separation, gives a Mn concentrate with the highest MnO% (89.26%) in comparison to the other two techniques for reduction roasting.

While the Fe_2O_3% content is decreased significantly from 21.86% in the ROM sample to only 3.32% in the non-magnetic concentrate reduced in a muffle furnace using a CO-CO_2 gas system, and to Fe_2O_3 3.84% in the sample reduced in a conventional furnace with charcoal as a reducing agent. Also, reduction in a microwave with charcoal gives a non-magnetic concentrate containing 4.99% Fe_2O_3.

Regarding the Mn/Fe ratio, it raised from only 2.81 in the ROM sample to 27 in the non-magnetic concentrate with a recovery of 93.90% while using the conventional reduction technique with a CO-CO_2 gas system as a source for reducing gas. Conventional reduction in a muffle furnace with charcoal as a reducing agent gives a non-magnetic concentrate with a Mn/Fe ratio of 25.70 and a recovery of 96.43%. On the other hand, microwave reduction of a sample with charcoal yields a non-magnetic concentrate with a Mn/Fe ratio of 19.82 and a recovery of 96.76 %.

These results clearly indicate that the three techniques for reduction roasting of such low-grade manganese ore (with Mn/Fe 2.81) are capable for producing high grade Mn concentrates containing both a high Mn/Fe ratio (19.82 – 27.45) and a high Mn recovery (93.89 – 96.76%). Moreover, it seems that the selectivity of magnetic separation (after the reduction process) between MnO and Fe_3O_4 (magnetite) phases is much better in comparison to that between MnO and Fe_2O_3 (hematite) phases. This is expected since, as mentioned above, magnetite has high magnetic susceptibility in comparison to hematite (**Chatterjee, 2010; Jang et al., 2014**). Also, the best reducing agent used is the gas (CO-CO_2) system where it gave better reduction results than using solid reducing agents (such as charcoal or coal). This is in agreement with the work of **Larssen, et al. (2021)**.

However, the results clearly indicate that the reduction of Mn ore in a microwave (even while using a solid reducing agent) gave superior results in terms of grade (highest MnO% 89.26) and high recovery (96.76%). This could be related to the fact that conventional thermal treatment depends on the use of electrical power-based furnaces with an outside-inside heating process. The microwave thermal treatment depends on vibrating inner molecules and produces heat from the inside to the outside of a sample (**Omran, et al. 2014; Li et al, 2020**).

3.3.2. X-ray diffraction (XRD) analysis of manganese concentrates

XRD results (see **Figure 6**) of manganese concentrates show that the peak patterns and semi-quantitative percentages of the presented minerals are changed in comparison to the ROM sample, as a result of the reduction roasting process, as follows (see **Table 3**):

a) XRD of manganese concentrate obtained after reduction roasting in a muffle with a CO/CO_2 system (see **Figure 6a**) shows that the majority of manganese oxides reduced into manganosite (~ 91.2% MnO) (PDF No. 96-600-6661) while ~ 8.8% remains as pyrolusite (MnO_2).

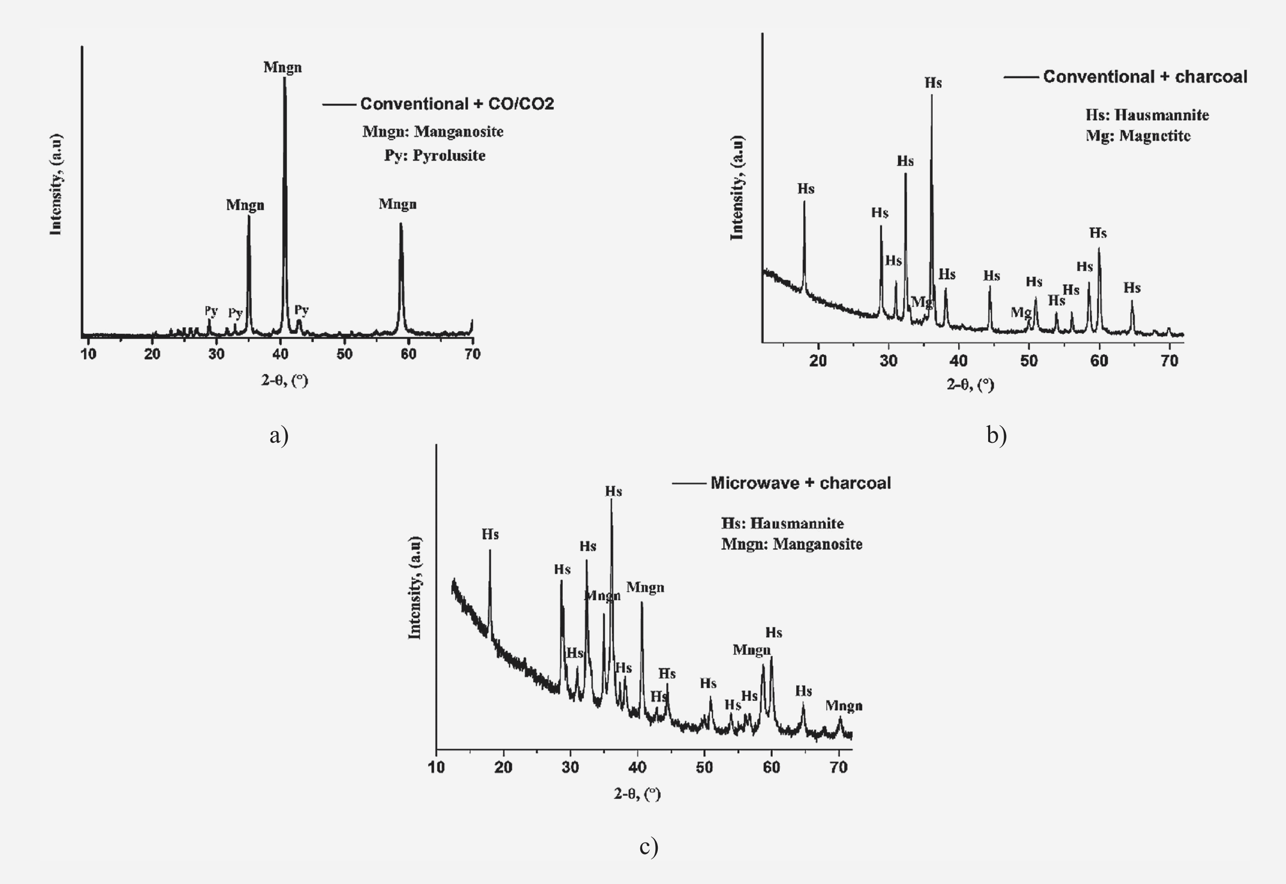

Figure 6: X-ray diffraction of the three manganese concentrate samples. (a) conventional + CO/CO_2. (b) conventional + charcoal. (c) microwave + charcoal.

Table 3: X-ray diffraction's semi-quantitative analysis of identified phases % in concentrates after reduction-roasting and magnetic separation

Sample	Manganosite (wt. %) (PDF No. 96-600-6661)	Hausmannite (wt. %) (PDF No. 96-101-1263)	Pyrolusite (wt. %) (PDF No. 96-900-9083)	Magnetite (wt. %) (PDF No. 96-901-3536)
Conventional + CO/CO_2	91.20	--	8.80	--
Conventional + charcoal	--	98.00	--	2.00
Microwave + charcoal	23.10	76.90	--	--

On the other hand, the reduction roasting in a microwave with charcoal (see **Figure 6c**) produces manganosite with a relatively lower Mn percentage (~23.10% MnO).

b) Hausmannite (Mn_3O_4) (PDF No. 96-101-1263) is the essential manganese mineral identified in XRD patterns after reduction roasting using charcoal, as a reducing agent, both in a conventional muffle (see **Figure 6b**) (~ 98% Mn_3O_4) or in a microwave (see **Figure 6c**) (~ 76.9% Mn_3O_4).

c) Magnetic separation after reduction roasting is a successful process for separating (as magnetic fractions) the majority of magnetite (Fe_3O_4) (PDF No. 96-901-3536) phase formed during the reduction with the three different reduction roasting techniques, where traces of Fe_3O_4 (~2%) are detected only in the concentrate obtained from reduction in a muffle with charcoal (see **Figure 6b**).

3.4. Flowsheet for beneficiation of low-grade manganese ore

A suggested tentative flowsheet was designed (see **Figure 7**), to manage the beneficiation process for such a ferruginous manganese ore. As the first step, the ROM sample is subjected to comminution (primary crushing and secondary crushing). Then, the crushed ore is directed to the grinding step in a closed circuit of screen (250

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 89-100, DOI: 10.17794/rgn.2024.5.6

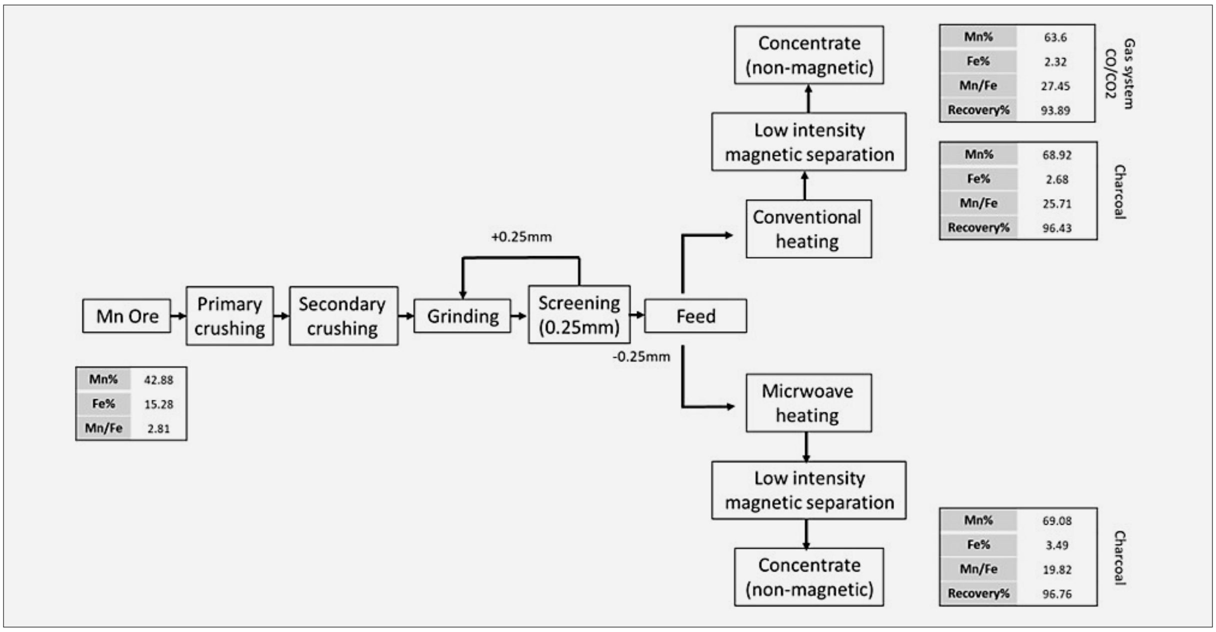

Figure 7: Flowchart for the beneficiation of Um Bogma manganese ore

Table 4: Comparison between the three reduction roasting techniques

	Conventional heating + CO/CO_2 gas system	**Conventional heating + charcoal**	**Microwave heating + charcoal**
Type of energy	Electrical	Electrical	Microwave (green energy)
Energy consumption	High	High	Low
Time [hr]	2.0	2.0	0.13
Cost	Very high	High	Cheap
Mn [%]	63.60	68.92	69.08
Fe [%]	2.32	2.68	3.49
Mn/Fe ratio	27.45	25.70	19.80
Recovery [%]	93.86%	96.43%	96.76%

µm) to yield a ground product (100%) beneath the estimated liberation size (-250 µm). This represents the feed to beneficiation tests (reduction roasting followed by magnetic separation) using one of the following routes:

1 – The conventional reduction roasting in a muffle using either a gaseous reducing agent (CO/CO_2 gas system) or a solid reducing agent (charcoal), both reduction techniques should be followed by the application of low-intensity magnetic separation for the reduced samples.

2 – Reduction roasting in a microwave with charcoal (as a solid reducing agent) followed by the application of low-intensity magnetic separation for the reduced ore.

Table 4 represents a comparison between applying conventional reduction techniques (in a muffle) and using a microwave for reduction roasting. These results illustrate that the conventional methods led to high Mn/Fe ratios up to 27.45 but this was achieved after 2.0 hr. While the microwave technology achieves good results as it led to a Mn/Fe ratio of 19.80 with very high recovery of 96.76% after only 0.13 hr. In addition, it represents a green and novel technology (**Amankwah & Pickles, 2005; Omran et al., 2014; Zhao et al., 2014; Elmahdy et al., 2015; Omran et al., 2015b; Celikdemir et al., 2016; Chen et al., 2017; Omran et al., 2018; Li et al., 2020; Lin et al., 2021; Zhou et al., 2021**), since it caused a reduction in energy consumption as it needs a very short time for the reduction roasting process (0.13 hr. instead of 2.0 hr.) which reduced cost as well (**Zhou et al., 2022**).

4. Conclusions

Um Bogma manganese ore, characterized as ferruginous with a low Mn/Fe ratio of 2.81, is not directly suitable for industrial use, which requires a higher Mn/Fe ratio above 5. This study investigated methods to improve the suitability of the ore through beneficiation processes. The primary mineralogical components of Um

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 89-100, DOI: 10.17794/rgn.2024.5.6

Bogma manganese ore include pyrolusite (MnO_2), hematite (Fe_2O_3), and manganite (MnO(OH)). The research focused on reduction roasting techniques aimed at transforming ferruginous mineral phases into magnetite (Fe_3O_4), a ferromagnetic phase that can be efficiently separated from paramagnetic manganese phases via low-intensity magnetic separation. The study evaluated the efficacy of both conventional and microwave heating methods, identifying optimal conditions at 700-800°C. Conventional heating required 2 hours, whereas microwave heating needed only 0.13 hours at 1.5 kW power. The optimal proportions of reducing agents were determined to be 20% for both CO/CO_2 and charcoal. The results revealed that all reduction roasting techniques followed by magnetic separation produced high-grade manganese concentrates, with Mn/Fe ratios between 19.8 and 27.0 and Mn recovery rates ranging from 93.89% to 96.76%. The $CO\text{-}CO_2$ gas system yielded a higher Mn/Fe ratio of 27.45 compared to the 25.70 ratio achieved with charcoal, though the latter is more economically viable for industrial applications. Additionally, reduction roasting with CO/CO_2 in a muffle converted most of the manganese into manganosite (~91.2% MnO). In contrast, using charcoal as a reducing agent in a conventional muffle produced mainly hausmannite (~98% Mn_3O_4), while microwave reduction resulted in a mix of hausmannite (~77% Mn_3O_4) and manganosite (~23% MnO). Microwave reduction, even with solid reducing agents, demonstrated significant results, achieving high MnO content (89%) and high recovery rates (~97%). This method also presents benefits in terms of energy efficiency, cost savings, and reduced processing time. However, further research into optimizing microwave heating parameters to enhance efficiency is a promising avenue.

5. References

Ahmed A. A. (1977): Studies on the beneficiation of El-Bahariya iron ore in Egypt, M.Sc Thesis, Faculty of Engineering, Assuit University.

Amankwah, R. K., & Pickles, C. A. (2005): Microwave calcination and sintering of manganese carbonate ore. In Canadian Metallurgical Quarterly (Vol. 44, Issue 2, pp. 239–248). Metallurgical Society of CIM. https://doi.org/10.1179/cmq.2005.44.2.239

Araffa, A. S., Rabeh, T. T., Mousa, E. A., Abdel Nabi, H., & Al Deep, M. (2020): Integrated geophysical investigation for mapping of manganese-iron deposits at Wadi Al Sahu area, Sinai, Egypt-a case study. Arabian Journal of Geosciences 13: 823.

Astuti, W., Mufakhir, F. R., Prasetyo, E., Yuda, A. P. T., Sumardi, S., Nurjaman, F., Supriyatna, Y. I., Handoko, A. S., & Suharto. (2019): Effect of ore mineralogy on the reductive-leaching of manganese ores. IOP Conference Series: Materials Science and Engineering, 478(1). https://doi.org/10.1088/1757-899X/478/1/012014

Celikdemir, M., Sarikaya, M., Depci, T., & Aydogmus, R. (2016): Influence of Microwave Heating and Thermal Auxiliary on Decomposition of Siderite. IOP Conference Series: Earth and Environmental Science, 44(5). https://doi.org/10.1088/1755-1315/44/5/052002

Chartterjee, A. (2010): Sponge iron production by direct reduction of iron oxide. New Delhi: PHI Learning Ltd.

Chen, J., Li, L., Chen, G., Peng, J., & Srinivasakannan, C. (2017): Rapid thermal decomposition of manganese ore using microwave heating. Journal of Alloys and Compounds, 699, 430–435. https://doi.org/10.1016/j.jallcom.2016.12.379

Dawei. Y., Mingqian, Z., Utigard, T., Barati, M. (2014) TG/DTA study on the carbon monoxide and graphite thermal reduction of a high-grade iron nickel oxide residue with the presence of siliceous gangue. Thermochimica Acta. 575 (2014) 1–11.

Dan, Z., Zhang, Y., Cai, J., Li, X., Duan, N., & Xin, B. (2016): Reductive leaching of manganese from manganese dioxide ores by bacterial-catalyzed two-ores method. International Journal of Mineral Processing, 150, 24–31. https://doi.org/10.1016/j.minpro.2016.03.007

El Aref, M., Abd El-Rahman, Y., Zoheir, B., Surour, A., Helmy, H. M., Abdelnasser, A., Ahmed, A. H., & Ibrahim, M. El-A., (2020): Mineral Resources in Egypt (I): Metallic Ores, Egyptian Manganese Deposits, Chapter 14.9, Springer Nature Switzerland AG.

El-Faramawy, H., Eissa, M., Ghali, S. N., Mattar, T., Ahmed, A., El-Fawakhry, M., & Kotb, E. M. (2022): Silicomanganese alloy from rich manganese slag produced from Egyptian low-grade manganese ore. The Journal of the Southern African Institute of Mining and Metallurgy, 122. http://dx.doi.org/10.17159/2411-9717/1648/2022

El-Geassy, A. A., Nasr, M. I., Yousef, M. A., Khedr, M. H., & Bahgat, M. (2000): Behaviour of manganese oxides during magnetizing reduction of Baharia iron ore by CO-CO2 gas mixture. Ironmaking and Steelmaking, 27(2), 117–122. https://doi.org/10.1179/030192300677417

El-Hussiny, N. A., Abd El-Gawad, H. H., Mohamed, F. M., & Shalabi, M. E. H. (2016): Pyrolusite (MnO2) Quartz Calcite Reduction low grade Egyptian manganese ore by carbon of coke breeze in the form pellets. http://www.ijser.org

El-Shafei, S., Ramadan, F., Essawy, M., Henaish, A., & Nabawy, B. (2022): Geology, mineralogy and geochemistry of manganese ore deposits of the Um Bogma Formation, south-western Sinai, Egypt: Genesis implications. Mining of Mineral Deposits, 16(3), 86–95. https://doi.org/10.33271/mining16.03.086

Fahim, M. S., El Faramawy, H., Ahmed, A. M., Ghali, S. N., & Kandil, A. E. H. T. (2013): Characterization of Egyptian Manganese Ores for Production of High Carbon Ferromanganese. Journal of Minerals and Materials Characterization and Engineering, 01(02), 68–74. https://doi.org/10.4236/jmmce.2013.12013

Galal M. F., (2002): "Beneficiation process of El-Bahariya iron ore ". M.Sc Thesis, Faculty of Engineering, Assuit University.

Gao, L., Liu, Z., Pan, Y., Feng, C., Ge, Y., & Chu, M. (2020): A study on separation of Mn and Fe from high-alumina ferruginous manganese ores by the carbothermal roasting reduction process. Advanced Powder Technology, 31(1), 51–60. https://doi.org/10.1016/j.apt.2019.09.036

Gao, Y. B., Kim, H. G., & Sohn, H. Y. (2012): Kinetics of pre-reduction of manganese ore by CO. Transactions of the Institutions of Mining and Metallurgy, Section C: Mineral Processing and Extractive Metallurgy, 121(2), 109–116. https://doi.org/10.1179/1743285512Y.0000000003

Jang K.O., Nunna V.R.M., Hapugoda S., Nguyen A.V., Bruckard W.J. (2014): Chemical and mineral transformation of a low-grade goethite ore by dehydrroxylation, reduction roasting and magnetic separation. Mineral Engineering. 60: 14-22, https://doi.org/10.1016/j.mineng.2014.01.021

Kordi, M., Morad, S., Turner, B., & Salem, A. M. K. (2017): Sequence stratigraphic controls on formation of dolomite: Insights from the Carboniferous Um Bogma Formation, Sinai-Egypt. Journal of Petroleum Science and Engineering, 149, 531–539.

Larssen, T. A., Senk, D., & Tangstad, M. (2021): Reduction of Manganese Ores in CO-CO2 Atmospheres. Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science, 52(1), 363–381. https://doi.org/10.1007/s11663-020-02018-0

Lei, M., Ma, B., Lv, D., Wang, C., Asselin, E., & Chen, Y. (2021): A process for beneficiation of low-grade manganese ore and synchronous preparation of calcium sulfate whiskers during hydrochloric acid regeneration. Hydrometallurgy, 199. https://doi.org/10.1016/j.hydromet.2020.105533

Li, K., Chen, J., Peng, J., Omran, M., & Chen, G. (2020): Efficient improvement for dissociation behavior and thermal decomposition of manganese ore by microwave calcination. Journal of Cleaner Production, 260. https://doi.org/10.1016/j.jclepro.2020.121074

Liu, B., Zhang, Y., Lu, M., Su, Z., Li, G., & Jiang, T. (2019): Extraction and separation of manganese and iron from ferruginous manganese ores: A review. In Minerals Engineering (Vol. 131, pp. 286–303). https://doi.org/10.1016/j.mineng.2018.11.016

Moustafa, A.G., Abdel-Khalek, N.A., Sharaf-Eldin, A.A., Soltan, A.M., & Hassan, El-Sayed R. E. (2024): Characterization of some Um Bogma manganese ores in Um Bogma area and their potentiality upgrading and manufacturing of manganese alloys. Egyptian Journal of Geology.

Mpho, M., Samson, B., & Ayo, A. (2013): Evaluation of reduction roasting and magnetic separation for upgrading Mn/Fe ratio of fine ferromanganese. International Journal of Mining Science and Technology, 23(4), 537–541. https://doi.org/10.1016/j.ijmst.2013.07.012

Omran, M., Fabritius, T., Elmahdy, A. M., Abdel-Khalek, N. A., El-Aref, M., & Elmanawi, A. E. H. (2014): Effect of microwave pre-treatment on the magnetic properties of iron ore and its implications on magnetic separation. Separation and Purification Technology, 136, 223–232. https://doi.org/10.1016/j.seppur.2014.09.011

Omran, M., Fabritius, T., Elmahdy, A. M., Abdel-Khalek, N. A., & Gornostayev, S. (2015): Improvement of phosphorus removal from iron ore using combined microwave pretreatment and ultrasonic treatment. Separation and Purification Technology, 156, 724–737. https://doi.org/10.1016/j.seppur.2015.10.071

Omran, M., Fabritius, T., & Mattila, R. (2015): Thermally assisted liberation of high phosphorus oolitic iron ore: A comparison between microwave and conventional furnaces. Powder Technology, 269, 7–14. https://doi.org/10.1016/j.powtec.2014.08.073

Ravisankar, V.; Venugopal, R. & Harikrishna, B. (2017): Investigation on beneficiation of goethis -rich iron ores using reduction roasting followed by magnetic separation. Mineral Processing and Extraction Metallurgy, Section C. Dec.2017, DOI: 10.1080/03719553.2017.1412876

Rath, S. S., Tripathy, S. K., Rao, D. S., & Biswal, S. K. (2018): Characterization and Reduction Roasting Studies of an Iron Rich Manganese Ore. Transactions of the Indian Institute of Metals, 71(4), 861–872. https://doi.org/10.1007/s12666-017-1218-3

Sallam, O. R. (2020): Origin of Mn-Fe ore bearing radioactive minerals at Um Bogma area, Southwestern Sinai, Egypt. Nuclear Sciences Scientific Journal, 9, 79- 102

Sharma,T. (1992): Physicochemical processing of low grade manganese ore. International Journal of Mineral Processing, 35 (1992) 191-203.

Singh, V., Biswas, A., & Sahu, N. (2020): Development of a Smelting Reduction Process for Low-Grade Ferruginous Manganese Ores to Produce Valuable Synthetic Manganese Ore and Pig Iron. https://doi.org/10.1007/s42461-020-00271-0/Published

Singh, V., Chakraborty, T., & Tripathy, S. K. (2020): A Review of Low Grade Manganese Ore Upgradation Processes. In Mineral Processing and Extractive Metallurgy Review (Vol. 41, Issue 6, pp. 417–438). Taylor and Francis Inc. https://doi.org/10.1080/08827508.2019.1634567

Singh, V., Reddy, K. V., Tripathy, S. K., Kumari, P., Dubey, A. K., Mohanty, R., Satpathy, R. R., & Mukherjee, S. (2021): A sustainable reduction roasting technology to upgrade the ferruginous manganese ores. Journal of Cleaner Production, 284. https://doi.org/10.1016/j.jclepro.2020.124784

Sinha, M. K., Purcell, W., & Van Der Westhuizen, W. A. (2020): Recovery of manganese from ferruginous manganese ore using ascorbic acid as reducing agent. Minerals Engineering, 154. https://doi.org/10.1016/j.mineng.2020.106406

Tang, Q., Zhong, H., Wang, S., Li, J. Z., & Liu, G. Y. (2014): Reductive leaching of manganese oxide ores using waste tea as reductant in sulfuric acid solution. Transactions of Nonferrous Metals Society of China (English Edition), 24(3), 861–867. https://doi.org/10.1016/S1003-6326(14)63136-8

USGS (2023): Mineral Commodity Summaries: Manganese. U.S. Geological Survey Publications Warehouse.

Wan, J., Chen, T., Zhou, X., Luo, Y., Liu, W., & Lu Q. (2021): Efficient improvement for the direct reduction of high-iron red mud by co-reduction with high-manganese iron ore. Minerals Engineering. 174,107024. https://doi.org/10.1016/j.mineng.2021.107024

Wang, Y., Jin, S., Lv, Y., Zhang, Y., & Su, H. (2017): Hydrometallurgical process and kinetics of leaching manganese from semi-oxidized manganese ores with sucrose. Minerals, 7(2). https://doi.org/10.3390/min7020027

Yi, L., Huang, Z., Jiang, T., Zhao, P., Zhong, R., & Liang, Z. (2017): Carbothermic reduction of ferruginous manganese ore for Mn/Fe beneficiation: Morphology evolution and separation characteristic. Minerals, 7(9). https://doi.org/10.3390/min7090167

Yoshikawa, N. (2018): Microwave Processing of Metallic Materials. IOP Conference Series: Materials Science and Engineering, 424(1). https://doi.org/10.1088/1757-899X/424/1/012041

Youssef, M.A. & Abdel-Khalek, N.A. (2011): Amenability of recycling of manganese from ferromanganese plant wastes using conventional and bio-processing techniques. Internal Report. CMRDI.

Zhang, Y. bo, Zhao, Y., You, Z. xiong, Duan, D. xian, Li, G. hui, & Jiang, T. (2015): Manganese extraction from high-iron-content manganese oxide ores by selective reduction roasting-acid leaching process using black charcoal as reductant. Journal of Central South University, 22(7), 2515–2520. https://doi.org/10.1007/s11771-015-2780-7

Zhao, W., Chen, J., Chang, X., Guo, S., Srinivasakannan, C., Chen, G., & Peng, J. (2014): Effect of microwave irradiation on selective heating behavior and magnetic separation characteristics of Panzhihua ilmenite. Applied Surface Science, 300, 171–177. https://doi.org/10.1016/j.apsusc.2014.02.038

Zhou, W., Sun, Y., Han, Y., Gao, P., & Li, Y. (2021): Recycling iron from oolitic hematite via microwave fluidization roasting and magnetic separation. Minerals Engineering 164-106851. https://doi.org/10.1016/j.mineng.2021.106851

Zhou, W., Sun, Y., Han, Y., Gao, P., & Li, Y. (2022): Mechanism of microwave assisted suspension magnetization roasting of oolitic hematite ore. Journal of Central South University 29, 420–432. DOI: https://doi.org/10.1007/s11771-022-4937-5

SAŽETAK

Oplemenjivanje željezne rude mangana s lokaliteta Um Bogma, Sinaj: usporedba konvencionalnih tehnika redukcijskoga prženja i mikrovalne tehnologije

Sve veća potražnja za visokokvalitetnim manganskim rudama u raznim industrijama dovela je do rastuće potrebe za poboljšanjem kvalitete niskokvalitetnih manganskih ruda. Reprezentativni uzorak manganske rude prikupljen je iz Um Bogme, Sinaj, u Egiptu, i podvrgnut je različitim metodama karakterizacije uključujući rendgensku difrakciju (XRD), rendgensku fluorescenciju (XRF) te rudnu mikroskopiju. XRF analiza uputila je nizak omjer Mn/Fe od 2,81 (kao elementi), što upućuje na nizak sadržaj rude. Za prikladnost u proizvodnji Mn legura u tvornici Sinai Manganese Company (SMC) u Abu Zenimahu, jugoistočno od Sinaja u Egiptu, ovaj bi omjer idealno trebao biti iznad 5. Dodatno, XRD analiza i rudna mikroskopija determinirali su mineraloški sastav rude kao piroluzit, hematit, i manganit, s manganskim masama ugrađenim u željezni matriks na teksturalnoj razini. Korištene su tri različite tehnike redukcijskoga prženja, koje uključuju konvencionalno zagrijavanje u peći uz korištenje ili CO – CO_2 ili drvenoga ugljena kao redukcijskoga sredstva, uz redukcijsko prženje drvenim ugljenom korištenjem mikrovalne tehnologije. Nakon svake tehnike primijenjena je magnetska separacija, što je rezultiralo proizvodnjom visokokvalitetnih koncentrata mangana koji pokazuju visoke omjere Mn/Fe u rasponu od 19,80 do 27,45 i znatne stope iskorištenja Mn u rasponu od 93,86 % do 96,76 %.

Ključne riječi:
manganska ruda, Um Bogma, oplemenjivanje, mikrovalno grijanje, redukcijsko prženje

Author's contribution

Ahmed Moustafa (1) (Demonstrator at Geology department, Faculty of Science, Ain Shams University) gathered rock samples, characterized samples and contributed in crushing, grinding, magnetic separation, and reduction roasting processes. **Nagui Abdel-Khalek (2)** (Emeritus Professor of Mineral Processing at CMRDI) evaluated the results, reviewed the draft manuscript, and provided technical suggestions. **Ahmed Sharaf-Eldin (3)** (Associate professor at Geology department, Faculty of Science, Ain Shams University) described the characterization and the evaluation of the final products, and evaluated the results, reviewed the draft manuscript, and provided technical suggestions. **Abdelmonem Soltan (4)** (Professor at Geology department, Faculty of Science, Ain Shams University) gathered rock samples, characterized samples, evaluated the results, reviewed the draft manuscript, and provided technical suggestions. **El-Sayed Hassan (5)** (Associate professor of Mineral Processing at CMRDI) contributed in crushing, grinding, magnetic separation, reduction roasting processes, and described the characterization and the evaluation of the final products.