



Wet gravity separation and froth floatation techniques for rare earth elements beneficiation from monazite ore in Jordan

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ABSTRACT

The demand for extracting Rare Earth Elements (REEs) from their deposits is growing significantly around the world since they are essential in many mature and growing industries. This study investigated the elemental and mineralogical composition of a Bulk sample and its potential for rare earth elements (REEs) beneficiation through Wet Gravity Separation (WGS) and Froth Floatation (FF) processes. Results obtained from WDXRF analysis showed that Si, Hf, Ti, Fe and Zr were the major elements present in the Bulk sample, with SiO₂ accounting for 64.79 wt%. The TREOs concentration was around 0.90 wt%, dominated by Ce, La, and Nd, with other REEs present in smaller concentrations. XRD analysis indicated that Quartz was the major mineral present in the Bulk sample. WGS and FF were then used to beneficiate the oxides CeO₂, La₂O₃, Nd₂O₃, Pr₆O₁₁, Y₂O₃, Gd₂O₃, and Sm₂O₃. Results showed significant concentration increases of these elements in the WGS concentrate, with high grade and good recoveries achieved for Ce, La, and Nd. Overall, the study provides insights into the potential of WGS and FF as a beneficiation technique for REEs in monazite ore.

1. Introduction

The Rare Earth Elements (REEs) are a group of 17 chemical elements; 15 are lanthanides (Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), and Lutetium (Lu)) in addition to Yttrium (Y) and Scandium (Sc) since they tend to occur in the same ore deposits as the lanthanides and exhibit similar chemical properties [1,2]. Except for the Pm, which has a radioactive nature, the REEs are relatively abundant in the earth's crust. The least abundant REE, Tm, is around 200 times more abundant than gold [3]. They are called "rare" because it is very unusual to find them concentrated in exploitable ore deposits, typically they tend to exist only as part of the host mineral's chemistry. They are also referred to as Rare Earth Oxides (REOs) as many of them are sold in oxide compound forms to meet specific downstream technology applications.

Based on the electron shell structure, REEs are categorized into two groups: The Light Rare Earth Elements (LREEs) group which includes La, Ce, Pr, Nd, Pm, Sm and Eu, the elements in this group commonly have an increasing 'unpaired' electron from 0 to 7. And the other group is the Heavy Rare Earth Elements (HREEs) which includes Y, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu, the elements in this group have 'paired' electrons (a clockwise and counter-clockwise spinning electron) [4–7]. It is worth mentioning that Scandium is not included in either the LREEs or HREEs classifications; when classified as an REE [1].

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These elements have gained immense attention in recent decades. They are used in mature industries (such as catalysts, glass-making, lighting, metallurgical applications and alloys), and in newer, fast-growing industries (such as battery alloys, ceramics and permanent magnets) as well as in industries related to clean energy solutions (such as wind turbines and smart-batteries that power every electric and hybrid vehicle) [8,9]. Their unique physical, chemical, magnetic and luminescent properties make them a potential candidate for utilization in many technological developments. Their technological applications in energy-efficient gadgets (which are faster, lighter, smaller and more efficient) have multiplied over the last decades and the demand for REEs production has rapidly increased [2,4,6]. The world's total mine production in 2021 increased to 280,000 tons of REOs; with a 21% increase in the last two years [10,11]. The domestic production of minerals concentrates in the United States and China increased to 43,000 and 168,000 tons, respectively, which combined is equivalent to more than 75% of the total production globally in 2021, [11].

REEs generally occur in uncommon geologic rock types and settings. There are two types of REEs deposits; primary deposits, which nowadays are the main source of REEs production, such as carbonatite associated deposits, Iron-REEs deposits and Alkaline Igneous rocks. And secondary deposits, which are considered as a minor production source, including Placer deposits, Weathering deposits (lateritic) and Ion Adsorption clays. Most REEs occur in ore deposits within minerals commonly classified as carbonates, oxides, halides, phosphates and silicates [12]. The main economically exploited rare earth minerals are Bastnasite, Loparite, Monazite, Xenotime, and the Lateritic Ion-Adsorption Clays [7]. It is worth mentioning that Monazite contains more LREEs compared to HREEs and are associated together with the Naturally Occurring Radioactive Materials (NORM); Thorium and Uranium, in significant concentrations [13,14]. On one hand, trivalent REEs have similar ionic radii to Ca^{2+} , Th^{4+} , U^{4+} , therefore the REE minerals are normally associated with Ca, Th, U, making the exploitation of REEs full of environmental challenges [6]. However, a large amount of uranium in rare earth deposits may be extracted as a by-product [15].

1.1. REEs in Jordan

Several exploration studies including geophysical, geological and geochemical surveys have been conducted in Jordan since 1979. These studies nurtured the growing interest in REEs prospecting. REEs are relatively abundant in the earth's crust, however, their existence in concentrations economically feasible to mine is less common than most of the other ores. A cooperation agreement was signed between the Ministry of Energy and Mineral Resources (MEMR) and the Jordan Atomic Energy Commission (JAEC) in April 2017 to evaluate the geological resources of REEs in the south of Jordan. The implementation of the exploration project for REEs began in May 2017 to outline and conduct a preliminary evaluation of the potential REEs resources in the south of Jordan; the entire area of the Dubaydib Formation (900 km² of the total area in the Wadi Al-Mazzarib region) was covered by this exploration project [16,17]. The study area is located about 350 km south of Amman and 100 km northeast of Aqaba as shown in Fig. 1.

The preliminary results of the project evaluation showed promising concentrations of REEs, as well as high concentrations of Zirconium, Titanium and NORMs such as Uranium and Thorium. According to previous geological studies, the target section of the Dubaydib formation bears Monazite mineral and Xenotime [17].

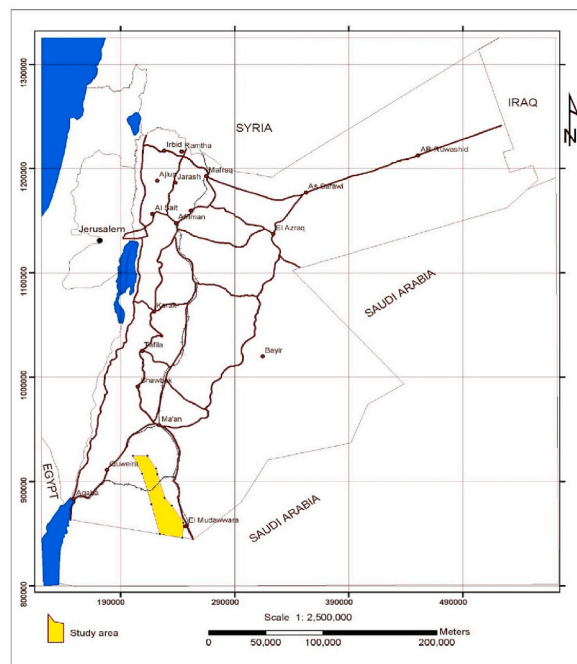


Fig. 1. Location map of the study area [17].

Generally, minerals hosting rare earth elements are not found in economical concentrations, they usually coexist with a wide range of other minerals with similar physical and chemical properties [1,18,19]. The primary REEs host minerals have been beneficiated hydrometallurgically by methods like Froth Flotation, Magnetic Separation, Electrostatic or Gravity Separation methods [13,20–22] on a commercial level to reduce impurities and produce concentrates with elevated concentrations of rare earth host minerals. On the other hand, due to the diversity and complexity of rare earth mineral deposits, it is very important to develop feasible beneficiation processes specifically for the rare earth mineralogy in the targeted deposits.

1.2. Wet gravity separation and froth flotation

Gravity separation is used in mineral processing to separate minerals based on differences in their specific gravity [23]. REEs are good candidates for the gravity separation method as they have relatively large specific gravities (4–7) and are typically associated with gangue minerals (primarily silicates) that is significantly less dense [1,12].

The flotation process is considered one of the most important techniques to separate rare earth minerals from associate minerals and is commonly applied to the beneficiation of rare earth ores. It is worth mentioning that this separation method is used to separate minerals by exploiting the differences in their surface wettability [12,24]. The particles become water repellent by coming in contact with moving air bubbles in the presence of certain reagents. The froth portion moves up leaving the gangue (tailing) below, which is then collected as a concentrate for further beneficiation, if necessary [1,12,25]. Many studies have been conducted on the REEs beneficiation through the Froth Flotation process [5,12,21,26–28]. Abaka-Wood et al. studied the physicochemical properties that influence the efficiency of Monazite flotation in the presence of oleic acid as a collector and the Froth Flotation process conditions used in this work were based on what they concluded in that study [29].

Moustafa et al. [14] employed a series of physical beneficiation processes; Wet Gravity Separation, Electrostatic and Magnetic Separation techniques to physically beneficiate the low grade (0.60 wt%) Egyptian black sands deposits along the Mediterranean coast. Jiao et al. [30] utilized the Froth Flotation technique to beneficiate the Dalucao rare earth ore located in Dechang, Sichuan Province, China (with an average grade of 2.40 wt%) yielding a concentrate with 20.19 wt% grade.

Narantsetseg [31] studied the beneficiation of rare earth ore of the Bokan Mountain: Dotson Ridge ore located near Ketchikan, Alaska using gravity concentration, Magnetic Separation and Froth Flotation. Narantsetseg managed to produce a 53% combined mass yield of the Gravity and Magnetic Separation processes.

In this paper, a laboratory-scale beneficiation procedure was assembled to employ the Wet Gravity Separation and the Froth Flotation techniques [12,14,21,32] to examine different beneficiation processes for the REEs concentrations in the Monazite deposits located at the south of Jordan to reach an efficient, viable and sustainable beneficiation process, and ultimately produce high-grade REEs concentrates with minimum produced tailings.

2. Materials and methods

A 9 kg Bulk sample, taken from a trench drilled in the Dubaydib Formation area, was used in this study. The sample was dried in the oven at a temperature around 105 °C overnight to ensure that the sample is free from any present humidity, and then crushed and ground to 125 µm particle size using a Jaw crusher then a Disk Mill at the physical sample preparation laboratory at JAEC. The 9 kg Bulk sample was then split into 1–1.5 kg subsamples for easier handling. Each subsample was mixed with water as a preparation for the Wet Gravity Separation process.



Fig. 2. Holman–Wilfley shaking table.

2.1. Wet gravity separation

Wet Gravity Separation (WGS) was performed after crushing the samples to a particle size less than 125 μm . The samples were beneficiated through the concentration of high specific gravity minerals such as REEs bearing minerals and the elimination of a significant portion of the low specific gravity minerals such as Quartz. WGS is a well-recognized method for beneficiation and it has been widely reported in previous studies, Moustafa et al. [14] employed a Wilfley shaking table to concentrate Monazite from Egyptian beach sand that contained valuable heavy minerals. Kim et al. [33] also used a Wilfley shaking table to remove the light gangue minerals, which mainly consisted of SiO_2 and Al_2O_3 from the sample. WGS method was applied on the water-subsample mix as an initial pre-concentration step using the Holman–Wilfley shaking table [34], shown in Fig. 2, to get rid of the low specific gravity gangue minerals.

Particles rich with minerals, from light to heavy and fine to coarse were sorted by their specific gravity. The water flow (on average around 6 L/min) was adjusted manually according to the amount of wet subsample mix left on the shaking table; the table tilt ranged between 5° and 7° . Three main outlets were connected to the shaking table; outlet number 1 for the particles with the lowest specific gravity, outlet number 3 with the densest particles that are expected to be rich with heavy minerals and outlet number 2 for particles with specific gravities in between those of the two other outlets (middling). The products from each outlet were gathered in a separate drum. The contents of each drum were processed on the shaking table for a second time to make sure that the particles were well separated based on their specific gravity.

The content of each drum was then collected and dried overnight at 105°C to make sure that they are free of humidity. Samples from each drum were then sent to the lab to be analyzed using ICP-OES technology.

2.2. Froth flotation

The Froth Flotation process was conducted using the DENVER D12 Flotation machine and a 5-Liter flotation cell was used. A sample of 250 g was processed by flotation at room temperature ($20\text{--}25^\circ\text{C}$). Warm distilled water was used for flotation, and a dosage of 1000 g/t of sodium silicate (produced by Ridel-de Haen with 18% Na_2O , 60% Silicic acid) was used as a depressant since it improves the REO upgrade by reducing the recovery of hematite and quartz gangue minerals [28,35]. A dosage of 1000 g/t of oleic acid (produced by Sigma-Aldrich, 65%–88% GC), which is a fatty acid that acts as a collector, was used [29,35]. The pH value of the mixture was adjusted using NaOH (Fluka Chemika, Sodium Hydroxide $\geq 98\%$). The impeller speed (ranged from 750 rev/min to 1300 rev/min), the air flow rate ($3.5\text{ dm}^3/\text{min}$), and the pH (9–10) were maintained during the whole flotation process. The foam formed was collected using a clean tray and then dried overnight at 105°C in a drying oven. The process flowsheet is presented in Fig. 3. Samples from the product of the flotation process were sent to the lab to be analyzed using the ICP-OES technique.

2.3. Chemical composition of the samples

2.3.1. Wavelength dispersive X-ray fluorescence analysis

The main elements in the Bulk sample were identified by Wavelength Dispersive X-ray Fluorescence (WDXRF) analysis was done using Bruker AXS. S4 Pioneer WDXRF spectrometer. Loss of Ignition (LOI) was determined after roasting 4 g of the homogenized sample at 1000°C for 6 h. Claisse Lithium Borate Flux (49.75% $\text{Li}_2\text{B}_4\text{O}_7$, 49.75% LiBO_2 and 0.5% LiBr) produced by Malvern Panalytical with a purity of 99.98% was used to produce the fused beads. The sample was mixed with the flux using a 1:7 ratio, then it was fused using Claisse, Inc. – M4 Fluxer. The generated fused beads were then labeled and analyzed using the WDXRF.

2.3.2. Inductively coupled plasma atomic emission spectroscopy

The ICP-OES technique is a feasible way for determining the REEs concentrations in complex samples because of the multi-element capacity, high specificity, precision, high accuracy and the fact that it exhibits a wide linear dynamic range [36–41]. At the end of each

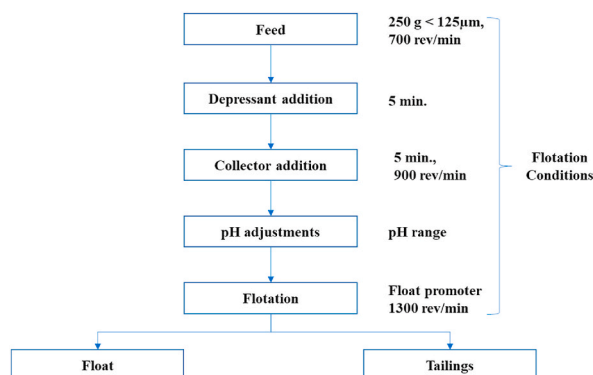


Fig. 3. Flotation process flowsheet.

beneficiation step, samples were taken from the product and analyzed using ICP-OES Thermo Fisher Scientific iCAP 6300 technology. A 0.15 g of the sample was acid digested at (150–175 °C) using (HNO₃(Biosolve, 70%), HF (Sigma-Aldrich, 48%), HClO₄ (GCC, 60%), H₃BO₃(Carlo Erba, 99%)) and diluted with ASTM water. The generated clear solution was then analyzed using the ICP-OES instrument.

It is worth mentioning that repeatability was measured by analyzing three duplicates for each tested sample. The three duplicate samples were analyzed for all beneficiation stages and the arithmetic mean of the analysis results for the three duplicates was used as the final results to avoid random errors. Reported measurement results were accompanied with Relative Standard Deviation (RSD); which is the ratio of standard deviation to the mean of the results from the three duplicates, as shown in Eq. (1):

$$\text{RSD}(\%) = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100\% \quad (1)$$

2.4. Mineralogical analysis

To determine the mineral composition, samples from both beneficiation steps as well as samples of the Bulk were analyzed by X-Ray Diffraction (XRD) technology. XRD analysis is an important technique used in identifying the minerals and their phases present in the samples [1,42,43]. The identification of mineralogy present in the samples was done using Bruker D4 Endeavor X-ray Diffractometer at the Laboratories of the Ministry of Energy and Mineral Resources. Cu-K α radiation at 40 kV and 40 mA was used to analyze the samples. The 2 θ incidence angles spanned from 5° to 70°.

2.5. Recovery calculations

The total REO (TREO) grade was calculated using Eq. (2).

$$\text{TREO} = \sum (c_{\text{CeO}_2}, c_{\text{La}_2\text{O}_3}, c_{\text{Pr}_6\text{O}_{11}}, c_{\text{Nd}_2\text{O}_3}, \dots) \quad (2)$$

where c_{CeO_2} is the grade of Cerium oxide in the concentrate, $c_{\text{La}_2\text{O}_3}$ is the grade of Lanthanum oxide in the concentrate, etc. However, a high grade of TREOs does not necessarily indicate a high-efficiency beneficiation process. Thus, to evaluate the efficiency of each beneficiation process, Eq. (3) was used to calculate the Recovery [24,35]:

$$\text{Recovery} = \frac{C_c}{F_f} \times 100\% \quad (3)$$

where C is the mass of the resultant concentrate, c is the grade of the valuable oxide in the concentrate, F is the mass of feed and f is the feed grade of the valuable oxide. Hence, the recovery of the TREOs is given by Eq. (4):

$$\text{Recovery}_{\text{TREOS}} = \frac{C \times \sum (c_{\text{CeO}_2}, c_{\text{La}_2\text{O}_3}, c_{\text{Pr}_6\text{O}_{11}}, c_{\text{Nd}_2\text{O}_3}, \dots)}{F \times \sum (f_{\text{CeO}_2}, f_{\text{La}_2\text{O}_3}, f_{\text{Pr}_6\text{O}_{11}}, f_{\text{Nd}_2\text{O}_3}, \dots)} \times 100\% \quad (4)$$

where c_{CeO_2} is the grade of Cerium oxide in the concentrate and f_{CeO_2} is the grade of Cerium oxide in the feed, etc.

Table 1
Major element composition in oxide (wt%) form as determined by WDXRF analyses.

Element	Concentration (wt%) ^a
SiO ₂	64.792 (0.2)
HfO ₂	6.861 (0.4)
TiO ₂	6.494 (0.7)
Fe ₂ O ₃	5.586 (0.7)
ZrO ₂	4.857 (0.7)
CaO	2.641 (0.8)
Al ₂ O ₃	1.138 (0.7)
K ₂ O	0.833 (1.3)
P ₂ O ₅	0.66 (3.3)
CeO ₂	0.412 (2.3)
La ₂ O ₃	0.218 (2.8)
Nd ₂ O ₃	0.198 (3.2)
ThO ₂	0.134 (1.0)
V ₂ O ₅	0.123 (1.8)
Y ₂ O ₃	0.074 (0.4)
MgO	0.034 (3.2)
UO ₂	0.0163 (1.1)
LOI	3.36 (1.1)

^a All reported values are means of three replicates with % relative standard deviation shown in parentheses.

3. Results and discussions

Table 1 presents the major elements in the Bulk samples, analyzed by WDXRF. The WDXRF results showed that the major elements in the Bulk samples were Si, Hf, Ti, Fe and Zr. It can be noted from the WDXRF results below that the Bulk sample is rich in SiO₂ with a grade of 64.79 wt%.

From **Table 1**, the mean value of detected elements (in oxide form) in the Bulk sample shows that the total TREOs concentration is around 0.90 wt%, and it is mainly dominated by the LREEs (Ce, La, and Nd). Other REEs were present with smaller concentrations, below the detection limit associated with the WDXRF technique. In this study, the ICP-OES analysis technique was used to detect the REEs of interest. The results of the ICP-OES analyses (**Table 2**) showed that the main REEs present in the Bulk sample are Ce, La, Nd, Pr, Sm, Gd and Y, with total REEs elemental concentration of 0.93 wt% (and 1.12 wt% in oxide form).

The XRD analysis pattern for the Bulk sample is shown in **Fig. 4**. The pattern indicates that Quartz is the major mineral present in the Bulk sample. This agrees with the WDXRF results which show that around 65% of the Bulk sample is silicon oxide. While a small peak for Rutile (mineral for TiO₂) can be detected, other minerals were not detected using XRD analysis as they are in low/trace concentrations so the intensities of their peaks are so weak/small that XRD cannot detect.

It is worth mentioning that the pattern of the peaks overlaps and the high intensity of the peaks corresponding to major minerals (such as Quartz) makes it hard to observe other smaller peaks.

The oxides CeO₂, La₂O₃, Nd₂O₃, Pr₆O₁₁, Y₂O₃, Gd₂O₃ and Sm₂O₃ were chosen to move forward with this study as major oxides to be beneficiated since they expressed accountable concentrations from early stages in the ICP-OES analyses results. The other identified REOs were either depleted or in trace concentrations.

3.1. Wet gravity separation

The elemental REEs concentrations of the WGS resultant are listed in **Table 3**.

Results in **Table 3** show the effectiveness of the WGS beneficiation process. Elements like Er, Ho, and Tb were not detectable in the bulk sample, yet they showed higher concentrations than other elements like Sc and Eu in the concentrate. That might be attributed to the higher density of the former elements (9.06, 8.8 and 8.2) g/cm³ than the latter (2.98, 5.24) g/cm³, respectively [44].

While the XRD patterns reflect the existence of Quartz as the major mineral in the Bulk sample, new peaks for Zircon (Zr, REEs) appeared in the resultant of the WGS process as shown in **Fig. 5**. It is worth mentioning that Zircon has a relatively high specific gravity (4.6–4.7) which is very close to the specific gravity of the Monazite [1].

According to the analyses results shown in **Table 4**, the TREOs concentration was increased from 1.12 wt% to 8.16 wt% (more than 7 folds) with an overall recovery of 84.3% of the TREOs in the Bulk sample.

The current beneficiation results using the WGS demonstrates higher quality outcomes when compared with the Moustafa et al. [14] study to obtain Monazite concentrate from the low grade raw beach black sands, using a combination of gravity, magnetic and electrostatic separation techniques. The raw sands contained 0.25 wt% Monazite, was screened and deslimed and then processed through wet gravity concentration using the Wilfley shaking tables, 42% of the tabled feed was recovered as concentrate, contained 0.59 wt% Monazite.

Table 2
ICP-OES results for REEs content in the bulk sample in ppm.

Element	Concentration (ppm) ^a
Ce	4181 (2.1)
La	2069 (1.6)
Nd	1552 (1.5)
Pr	422 (2.8)
Y	349 (1.9)
Gd	314 (0.7)
Sm	286 (2.5)
Dy	96 (1.9)
Yb	31 (1.2)
Sc	17 (1.9)
Eu	13 (3.5)
Lu	7 (1.1)
Er	BDL ^b
Ho	BDL ^b
Tb	BDL ^b
15 REEs Total (wt%)	0.93

^a All reported values are means of three replicates with % relative standard deviation shown in parentheses.

^b Below detection Limit.

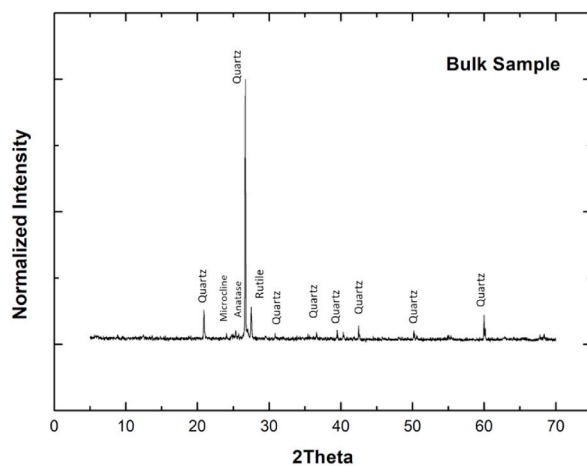


Fig. 4. The XRD pattern of the Bulk sample.

Table 3

ICP-OES results for REEs content in bulk, WGS Concentrate and Tails samples in ppm.

Element	Bulk (ppm) ^a	Concentrate (ppm) ^a	Tail 1 (ppm) ^a	Tail 2 (ppm) ^a
Ce	4181 (2.1)	30,138 (2.2)	1017 (2.0)	730 (2.9)
La	2069 (1.6)	15,646 (1.8)	412 (1.4)	296 (2.0)
Nd	1552 (1.5)	11,705 (1.1)	299 (3.4)	208 (1.0)
Pr	422 (2.8)	3021 (3.6)	104 (5.6)	BDL ^b
Y	349 (1.9)	2447 (2.0)	103 (0.9)	93 (0.9)
Gd	314 (0.7)	1594 (2.0)	163 (2.1)	133 (2.9)
Sm	286 (2.5)	2141 (3.7)	BDL ^b	BDL ^b
Dy	96 (1.9)	701 (2.9)	BDL ^b	BDL ^b
Yb	31 (1.2)	177 (1.2)	13 (1.5)	14 (1.4)
Sc	17 (1.9)	57 (1.8)	14 (1.7)	11 (0.5)
Eu	13 (3.5)	90 (2.2)	5 (4.4)	3 (0.8)
Lu	7 (1.1)	32 (1.8)	6 (2.6)	5 (4.1)
Er	BDL ^b	238 (0.9)	BDL ^b	BDL ^b
Ho	BDL ^b	107 (4.2)	BDL ^b	BDL ^b
Tb	BDL ^b	48 (12.8)	BDL ^b	BDL ^b

^a All reported values are means of three replicates with % relative standard deviation shown in parentheses.

^b Below Detection Limit.

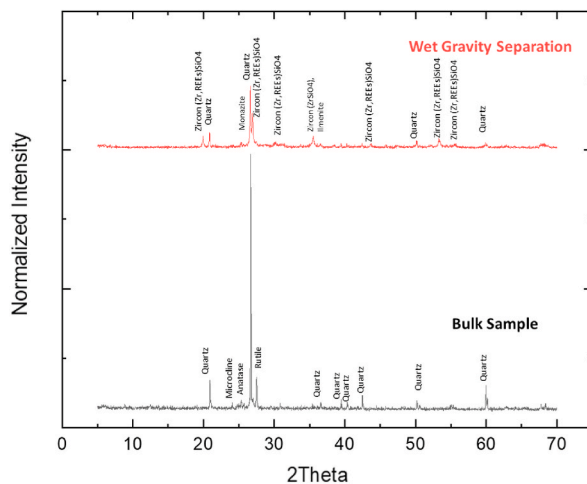


Fig. 5. The XRD pattern of the Bulk and the WGS resultant concentrate.

Table 4
Results of WGS beneficiation process.

Beneficiation Process		Feed	Concentrate	Tail 1	Tail 2 ^a	Losses
Wet Gravity Separation	Content wt% ^b	100	11.56	30.12	50.88	7.43
	TREOs (wt%)	1.12	8.16	0.18	0.26	–
	Recovery (%)	–	84.22	4.84	11.81	–

^a Only one tail was generated through the Froth Flotation process.

^b Content wt% represents the ratio of the weight of the product recovered to the total weight in the feed.

3.2. Froth flotation

The WGS resultant was then passed through the Froth Flotation process. The elemental REEs concentrations of the resultant are listed in Table 5.

As for the mineralogical analysis of the FF resultant; Fig. 6 shows the XRD patterns of the concentrate produced after FF process, which depicts the evolvement of the beneficiated sample mineralogy when compared with the mineralogy of the feed (WGS resultant). The decrement of the main Quartz peak intensity while new peaks for Monazite mineral emerging as its intensity increased is evident in the Froth Flotation XRD pattern. Furthermore, a closer examination shows that the presence of the rest of the gangue minerals like Rutile is insignificant with very low intensities.

The flotation process results show an efficient REOs selectivity since the REOs were concentrated within the float to achieve a TREOs concentration of 18.41 wt% with a recovery of 89.23% as shown in Table 6 below.

A comparison of all ICP-OES analyses results for samples through all stages (Bulk, WGS and FF) is depicted in Fig. 7. The beneficiation process started with 1.12 wt% of TREOs concentration and ended up with a concentration of 18.41 wt% indicating a very promising level of REEs beneficiation. While the gangue minerals were relatively concentrated within the resultant tailings.

The results showed that processing the Bulk samples through one method (WGS) will clearly beneficiate the concentration of the REEs and will result with a concentrate that contains an elevated concentration of REEs (about 7 folds) with a promising recovery of about 84%. However, processing the resultant concentrate through Froth Flotation doubles the concentration of the TREO in the concentrate. Light Rare Earth Elements were found in the final concentrate with a promising concentration; the cerium oxide concentration reached about 8 wt% while lanthanum oxide and neodymium oxide concentrations reached about 4 and 3.5 wt%, respectively.

Many studies on beneficiating REEs through the Froth Flotation process were reported in literature, Yang et al. [5] developed beneficiation process for a low grade REEs Olserum deposit. The process involved several beneficiation processes: grinding, wet low intensity magnetic separation, and three stages of REEs flotation. The study showed that the REE-bearing mineral, Monazite was successfully enriched from the concentration of 0.6 wt% in the feed to 17.0 wt% in the concentrate with the recovery of 79.0% which is comparable to the findings from the beneficiation process employing WGS and a single Froth Flotation stage, as outlined in this study. Abaka-Wood et al. [45] also investigated the possibility to produce rare earth elements – rich concentrate from an Australian complex low-grade saprolite ore (1.14 wt% TREO grade). Using desliming and subsequently Flotation processes on raw feed allowed the production of a concentrate with 5.87 wt% TREO grade, with a recovery of 45%. In the present study a greater concentrate grade and enhanced recovery is observed when compared with Abaka-Wood et al. [45] results. This suggests that relying solely on the froth flotation process, even after including preliminary processes like desliming, might not yield the desired concentrate. Hence, it is recommended to employ additional beneficiation processes like the WGS as suggested in this paper or even Magnetic Separation despite the recognized efficiency of Froth Flotation in REE beneficiation.

4. Conclusions

The beneficiation processes applied to samples from the Dubaydib deposits in south Jordan were successful in increasing the concentration of TREOs in the beneficiated samples. The WGS process recovered 84% TREO from the feed, and subsequent processing of the concentrate obtained via flotation recovered 89% TREO from the WGS concentrate. Processing the Bulk through Wet Gravity Separation and subsequently beneficiating the resultant concentrate through Froth Flotation increased the concentration of the TREO by more than 18 folds compared to Bulk ore. The resulting concentrate was dominated by Ce, La, and Nd, which have high concentrations compared to the other REEs present in the samples. Additionally, Zirconium was found in promising concentrations in the tails of the processes, which could be used as a byproduct of the beneficiation processes.

The successful production of REEs concentrates through beneficiation processes offers several benefits, including reduced transportation and handling costs and energy savings when compared to high energy-demanding separation operations of pyro or electric nature. However, operational parameter optimization analysis could be conducted in future projects to further increase the concentration in the treated samples and investigate the performance of the beneficiation processes for other different mineralogical structures. Furthermore, additional investigations are needed to include other beneficiation techniques to move towards the extraction step and develop appropriate commercial technology for separating the REEs individually.

Overall, the findings of this study demonstrate the applicability of the utilized beneficiation techniques in enriching the REEs hosted in the Monazite ore in the south of Jordan. Further research and development in this area could help secure a sustainable supply of critical REEs and contribute to the development of green technologies.

Table 5
Results of Froth Flotation beneficiation process.

Element	Bulk (ppm) ^a	Float (ppm) ^a	Tail (ppm) ^a
Ce	4181 (2.1)	69,270 (1.0)	3205 (1.5)
La	2069 (1.6)	34,945 (1.1)	1583 (0.7)
Nd	1552 (1.5)	27,873 (1.0)	1302 (2.5)
Pr	422 (2.8)	7186 (1.1)	336 (1.1)
Y	349 (1.9)	5045 (1.0)	839 (0.7)
Gd	314 (0.7)	3042 (1.1)	490 (6.7)
Sm	286 (2.5)	4931 (1.3)	242 (1.7)
Dy	96 (1.9)	1682 (1.1)	155 (0.9)
Yb	31 (1.2)	318 (1.0)	112 (0.9)
Sc	17 (1.9)	85 (1.8)	47 (1.7)
Eu	13 (3.5)	212 (1.0)	17 (0.6)
Lu	7 (1.1)	54 (1.3)	22 (1.6)
Er	BDL ^b	489 (1.3)	108 (1.2)
Ho	BDL ^b	247 (1.4)	27 (1.6)
Tb	BDL ^b	102 (2.8)	BDL ^b

^a All reported values are means of three replicates with % relative standard deviation shown in parentheses.

^b Below Detection Limit.

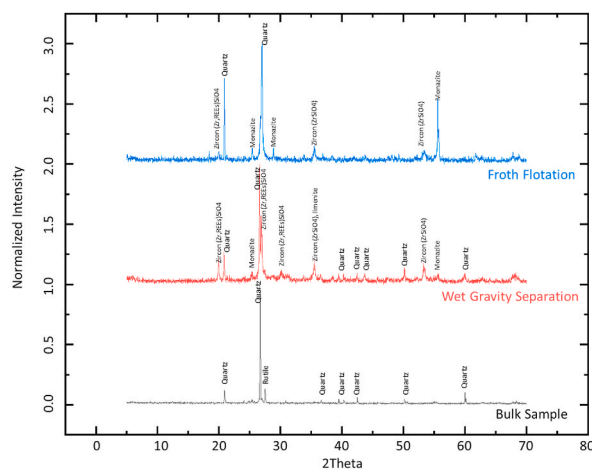


Fig. 6. The XRD pattern of the Bulk and the WGS and Froth Flotation resultant concentrate.

Table 6
Results of Froth Flotation beneficiation process.

Beneficiation process		Feed	Concentrate	Tail 1	Tail 2 *	Losses
Froth Flotation	Content wt% **	100	39.55	60.21	–	0.23
	TREOs (wt%)	8.16	18.41	1.28	–	–
	Recovery (%)	–	89.23	9.44	–	–

Author contribution statement

Ahmad Alsabbagh: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Rawan M. Mustafa: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.

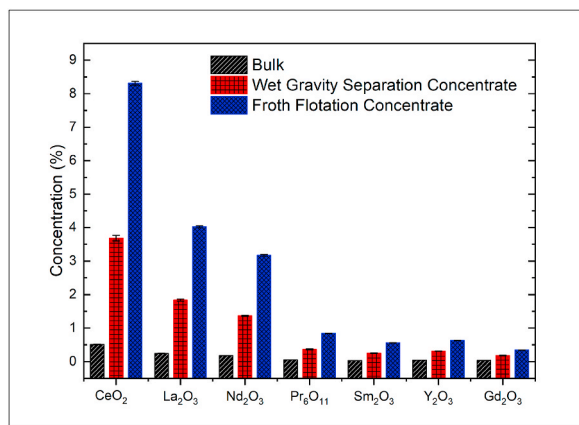


Fig. 7. ICP-OES beneficiation analysis results, the error bars representing the standard deviation of three duplicates.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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