

Influence of calcination conditions on deep eutectic solvents (DES) leaching efficiency of light rare earth elements in bastnasite ore

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ABSTRACT

In this century, our daily life is surrounded by technological devices, and Rare Earth Elements (REE) are at the heart of this technological revolution. They are always listed having the highest supply risk in critical minerals published by different countries. From that point of view, their extraction, and creating a secured supply chain is always crucial. In this research, the influence of calcination conditions on REE extraction from bastnasite ore was studied. Identical leaching in Ethylene Glycol (EG)-FeCl₃ media which is one of the Deep Eutectic Solvents (DES) was applied to different calcines to understand calcination parameters on leaching efficiency. After conducting experiments created by Box-Behnken approach with different parameters of temperature, duration, and particles size, the highest Light Rare Earth Elements (LREE) extraction efficiency of 67.22 wt% was achieved at 900 °C. However, while conducting control experiments, the highest extraction efficiency was found to be 75.986 wt% as a median of the experiments conducted at 500 °C during 180 min, and with particles finer than 25 μm. This efficiency increase with decreasing temperature is explained by Ce phase transformation from Ce₂O₃ to CeO₂ as proved by XRD analysis. In addition to temperature, particle size was also found highly effective in extraction efficiency especially in Ce extraction. At the experiments conducted at 900 °C, and 270 min but with particles at different size ranges, Ce extraction dramatically dropped from 71.061 wt% to 9.587 wt% at the experiment conducted with finer particles. This loss in efficiency is directly correlated to increasing Ce phase transformation rate due to increasing surface area of fine particles. Non-calcined ore was also leached with DES, and only 10.977 wt% LREE could be extracted. Furthermore, it is concluded that calcination is of vital importance to transform the ore into a soluble form, and temperature, and particle size ranges are found to be two fundamental parameters for tuning the extraction efficiency.

1. Introduction

The rare earth elements (REE) including scandium (Sc), yttrium (Y), lanthanum (La), and other elements found in the 4f-block of the periodic table, which are included in the “Critical Raw Materials” list by the European Commission, and are recognized for their limited utilization in material production while being capable of substantially improving material properties (European Commission et al., 2023). In nature, REE minerals such as bastnaesite, monazite, and xenotime are invariably found together, and those elements possess similar chemical properties.

Separating these elements from each other has been a challenging task due to their closely related electron configurations. However, it is possible to separate them because of difference in their basicity which is a result of mechanism called “lanthanide contraction” (Gupta, 2003; Gupta and Krishnamurthy, 2005).

The extraction of rare earth elements from the ore involves complex processes due to the complex geological formations and their close association with radioactive elements. In Turkey, there are four main rare earth element deposits, namely Kızılcaören (Sivrihisar-Eskişehir), Çanaklı (Isparta), Mortaş-Doğankuzu (Seydişehir-Konya), and Sofular

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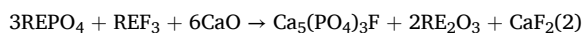
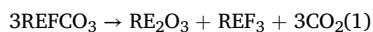
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(Malatya). The rare earth element content in the Kızılcaören ore deposit is approximately 30,000 ppm (Öztürk et al., 2019; Pirajno et al., 2019). The main minerals detected as fluorite, barite and bastnasite, which the content of the ore also has quartz, calcite, phlogopite, pyrolusite, and hematite, along with small amounts of plagioclase feldspar, pyrite, psilomelane, braunite, monazite, fluorapatite, brockite, goethite, and rutile (Gültekin et al., 2003). Bastnasite is the primary source of rare earth elements in the Kızılcaören deposit. In addition to bastnasite, monazite is another rare earth mineral in minor amount in the deposit (Kadir et al., 2016).

REE extraction flowsheet from ore has general steps such as crushing, grinding, calcination, leaching, purification (Solvent Extraction, Ion Exchange). To enhance the leaching process's efficiency, calcination is employed as a pre-treatment step for rare earth ore. It is applied to different REE containing resources such as ores (Huang et al., 2016; Xu et al., 2012; Zou et al., 2018), and coal residues (Ji et al., 2022; Li and Zhang, 2022; Pan et al., 2022; Zhang et al., 2020; Zhang and Honaker, 2019) etc. In the literature, it is known that bastnaesite ore undergoes calcination at 400 °C. Beyond 800 °C, the calcination of barite and monazite minerals takes place. It is known that no reaction at those temperatures occurs for the main phase, calcium fluoride (García et al., 2021, 2020). The calcination reactions of bastnaesite and monazite minerals are as follows respectively (1 and 2).



Since REEs were determined as critical minerals, extensive research on different topics like exploration new mining sites, recycling from secondary sources, developing efficient, and environmentally friendly extraction routes was conducted (Binnemans et al., 2013; Erust et al., 2023; Karshigina et al., 2018; Meshram and Abhilash, 2020; Sinclair et al., 2017). Traditional extraction methods often entail high energy consumption, extensive chemical use, and environmental pollution. Research efforts are focused on developing innovative extraction techniques that are more efficient, cost-effective, and environmentally friendly to meet the growing demand for rare earth elements in various industries. Deep eutectic solvents have emerged as a promising alternative for extracting rare earth elements from ores due to their low toxicity, biodegradability, and tunable properties (Smith et al., 2014). These solvents, composed of a hydrogen bond acceptor and a hydrogen bond donor, offer several advantages over traditional solvents, including their ability to selectively extract specific rare earth elements and operate at lower temperatures. The use of deep eutectic solvents in rare earth element extraction represents a sustainable approach that aligns with the industry's increasing focus on environmental responsibility. In literature, there are few studies applying this leaching method to REE ore sample. Entezari A., and Larachi F. have conducted one of these few studies. In their research, choline chloride-based DES were used, and concluded that DES is capable of separating higher, and lower Z number REE at initial step of metallurgical process (Entezari-Zarandi and Larachi, 2018).

In this study, for the first time in literature, the effect of calcination conditions on the leaching yield of Kızılcaören fluorite-barite-bastnasite ore using novel, and environmentally friendly Deep Eutectic Solvent leaching was explored, and calcination conditions giving the highest leaching yield were determined.

2. Materials and experimental Procedure

2.1. Materials and Equipment

The fluorite-barite-bastnasite complex ore used in the study was obtained from the Eskişehir-Kızılcaören REE deposit and supplied by the Institute of Rare Earth Elements Research (NATEN), affiliated by the Turkish Energy, Nuclear and Mining Research Agency (TENMAK).

Table 1

Chemical analysis of Light Rare Earth Elements (LREE) in Kızılcaören Fluorite-Barite-Bastnasite complex ore through particle size ranges used in the study.

Particle Size Ranges	La (wt. %)	Ce (wt. %)	Nd (wt. %)	Pr (wt. %)	Sm (wt. %)
+40 µm –180 µm	1.238	1.224	0.187	0.145	0.015
+25 µm –40 µm	2.375	2.122	0.353	0.270	0.027
– 25 µm	5.684	5.073	0.895	0.516	0.060

Table 1 presents the chemical analysis results of Light Rare Earth Elements (LREE) for Kızılcaören ore depending on particle size used in this study. A detailed investigation of the ore characteristic is another subject of the paper under review. For total elemental analysis of the ore, it was digested with Na₂O₂ (Merck 106,563 Supelco), and dissolved with HNO₃ (Merck 7697–37-2). Ethylene glycol (EG) (Merck 100949) and anhydrous FeCl₃ (Sigma-Aldrich 157740) chemicals were used during the leaching process. Ultrapure water was obtained from water purification system (IKA-Samrt2pure), and used in all experimental steps when required.

An oven (Nükleon) was used for drying purposes, a refractory furnace (NUVE MF 306) was used for calcination, and two different mixers (DLAB MS-H380-Pro and Daihan Scientific) were used for leaching processes. Chemical analysis of solid, and liquid samples was carried out by Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Thermo Scientific XSeries-II). X-Ray Diffractometry (Bruker™ AXS D8 Advance) device was used for phase analysis, and it was performed using CuKα radiation in the range of 10°–90° at a speed of 1°/min. The obtained patterns were matched with the latest ICSD cards using the X'pert High Score Plus software for phase determination.

2.2. Calcination experiments

In this part of the study, the ore was calcined at different experimental conditions. In each experiment, 1 g of sample in a ceramic crucible was calcined in pre-heated muffle furnace. Once calcination duration was completed, the sample was put into desiccator, and left to cool down to room temperature. The ore mass before, and after calcination was recorded to calculate the mass loss rate. Calcination experiments were modelled according to Box-Behnken approach with parameters given in Table 2, and with these parameters 15 experiments given in Table 3 were conducted. Two different responses were determined as REE extraction, and mass loss rate. Experimental results were evaluated by using Minitab software.

2.3. Deep Eutectic Solvents (DES) leaching

Following to calcination, all samples were subjected to identical leaching conditions to elaborate the influence of calcination parameter on leaching efficiency. In leaching process, EG was used as the medium instead of water. Oxidizing agent was 0.5 M FeCl₃, and the ore/solvent ratio was set to 20 g/L. The solution was stirred magnetically at 250 rpm, at 80 °C for 6 h. Extraction percentages were calculated by following formula. Total REE amount in each calcine was measured individually for better accuracy.

Table 2

Experimental parameters used in modelling.

Experiment Parameters	Coded Unit	–1	0	1
Particle Size Range (µm)	X ₁	–25	+25–40	+40–180
Temperature (°C)	X ₂	400	650	900
Duration (min.)	X ₃	60	270	480

Table 3
Calcination conditions.

S.N.	Particle Size Range (μm)	Temperature ($^{\circ}\text{C}$)	Duration (Min.)
1	+25–40	400	60
2	–25	400	270
3	+40–180	400	270
4	+25–40	400	480
5	–25	650	60
6	+40–180	650	60
7	+25–40	650	270
8	+25–40	650	270
9	+25–40	650	270
10	–25	650	480
11	+40–180	650	480
12	+25–40	900	60
13	–25	900	270
14	+40–180	900	270
15	+25–40	900	480

$$\text{REE Extraction Percentage (wt.\%)} = \frac{\text{REE amount in leachate}}{\text{Total REE amount in calcine}} \times 100$$

2.4. Determination of experimental modelling boundary conditions

For the ease of experimental results elaboration, and statistical evaluation, one of the response surface methodologies which is Box-Behnken approach was used in the current study (Box and Behnken, 1960). In this methodology, 3 levels of each factor are run, and the middle one of each factors is triplicated to ensure the accuracy of experimental design. Up to date, this method was used by several authors successfully in calcination, leaching or related fields (Gupta et al., 2024; Kondos and Demopoulos, 1993; Wang et al., 2023). That is why this method was chosen in this study. For calcination, 3 main parameters were selected as temperature, time, and particle size. For determining calcination temperature, a literature survey was made, and also DSC analysis was conducted to understand calcination temperature. Bastnasite transformation temperature was found to be 398 $^{\circ}\text{C}$ as seen from DSC analysis given in Fig. 1. Due to small amount of monazite present in the ore, no peak was detected related with its transformation at around 800 $^{\circ}\text{C}$ which is given as its calcination temperature in literature (García et al., 2021, 2020). With the information whether from analysis or from literature, calcination temperature range was determined as 400 $^{\circ}\text{C}$ –900 $^{\circ}\text{C}$ in calcination experiments. It should be noted that REE is highly

concentrated at fine particles in the ore especially below 25 μm in which concentration is almost quadrupled. 3 different particle size ranges as below 25 μm , 25–40 μm , 40–180 μm were chosen to be used in experiments. For calcination duration, the wide range from 60 min to 480 min was determined in order to understand the effect of time clearly on extraction efficiency.

3. Results and Discussion

3.1. Mass loss evaluation

The mass loss rates after the calcination are presented in Table 4 along with all other extraction efficiency data. In Fig. 2, all individual, and mean value of mass loss rate is presented., parameters from most effective to least effective can be ranked as temperature, particle size range, and time by looking the slope of mean value line, as seen in Fig. 2. Once individual results of experiment No:12, and 15 were examined for time influence on mass loss rate, it was seen that increasing calcination duration from 60 min. to 480 min. while temperature (900 $^{\circ}\text{C}$), and particle size (+25 μm –40 μm) were kept constant increased mass loss rate around 2 % (from 7.05 % to 8.97 %). Besides, once the same examination was done for experiments conducted at 400 $^{\circ}\text{C}$ (Experiment No: 1, and 4), mass loss rate increased only 0.24 % with increasing duration. This situation can be observed graphically by looking difference between the highest, and the lowest individual data points on 400 $^{\circ}\text{C}$, and 900 $^{\circ}\text{C}$ in Fig. 2. The same correlation is also valid for both particle size range, and duration. Due to the kinetic factors, increased temperature, and surface area resulted higher mass loss rate as expected.

Full quadratic regression equations, and their R-squared values are given in Table 5. The R-squared value of the regression line was 96.86 %, and a statistically significant 0.003p-value was obtained. This means that new experiments' mass loss rate within the boundary conditions can be predicted with high precision.

3.2. Evaluation of calcination parameters' influence on Deep Eutectic solvents (DES) leaching efficiency

Total LREE extraction, and individual LREE extraction efficiency results were given in Table 4. According to results in this table, experiment 15 has the lowest total LREE extraction efficiency. As the main purpose of the study was to determine calcination conditions of bastnasite ore, XRD patterns of two powders at the same particle size range as calcined with the parameters as in experiment no 15, and non-

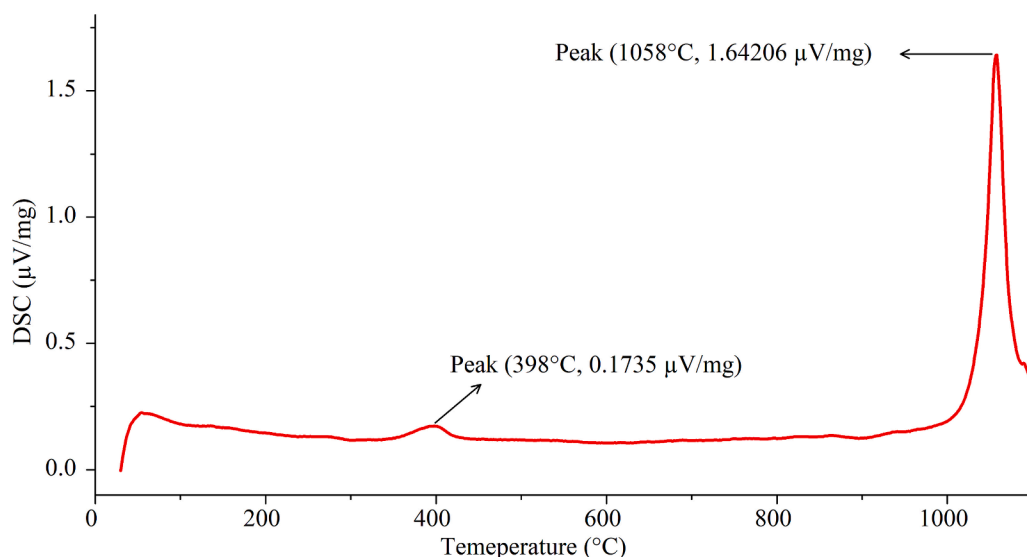


Fig. 1. DSC analysis of the ore.

Table 4
Experimental results after the calcination and Deep Eutectic Solvents (DES) leaching.

S.N.	Particle Size (μm)	Temp. ($^{\circ}\text{C}$)	Time (min.)	Mass Loss (%)	\sum LREE (%)	La (%)	Ce (%)	Nd (%)	Pr (%)	Sm (%)
1	+25–40	400	60	3.15	56.870	50.104	68.012	43.978	45.472	39.524
2	–25	400	270	3.91	56.773	48.495	68.948	47.539	48.580	41.827
3	+40–180	400	270	3.45	50.335	48.307	53.468	46.138	48.516	44.633
4	+25–40	400	480	3.39	61.263	52.608	74.100	50.774	53.031	47.166
5	–25	650	60	4.45	57.303	54.892	60.928	51.678	60.238	47.986
6	+40–180	650	60	5.56	46.424	45.973	45.520	54.134	57.454	57.572
7	+25–40	650	270	4.66	62.623	56.569	73.041	49.366	50.826	44.760
8	+25–40	650	270	4.46	62.764	60.313	68.131	52.817	54.372	47.440
9	+25–40	650	270	4.88	59.837	58.257	64.113	50.195	52.113	45.478
10	–25	650	480	6.87	67.107	60.714	77.640	54.320	56.314	50.313
11	+40–180	650	480	3.16	52.018	44.237	62.714	45.258	47.567	44.568
12	+25–40	900	60	7.05	43.998	52.049	33.799	45.661	47.422	43.215
13	–25	900	270	10.27	47.820	74.411	9.587	71.613	74.704	65.218
14	+40–180	900	270	5.16	67.222	64.832	71.061	61.253	63.550	66.959
15	+25–40	900	480	8.97	31.925	48.313	7.828	48.229	56.124	46.640

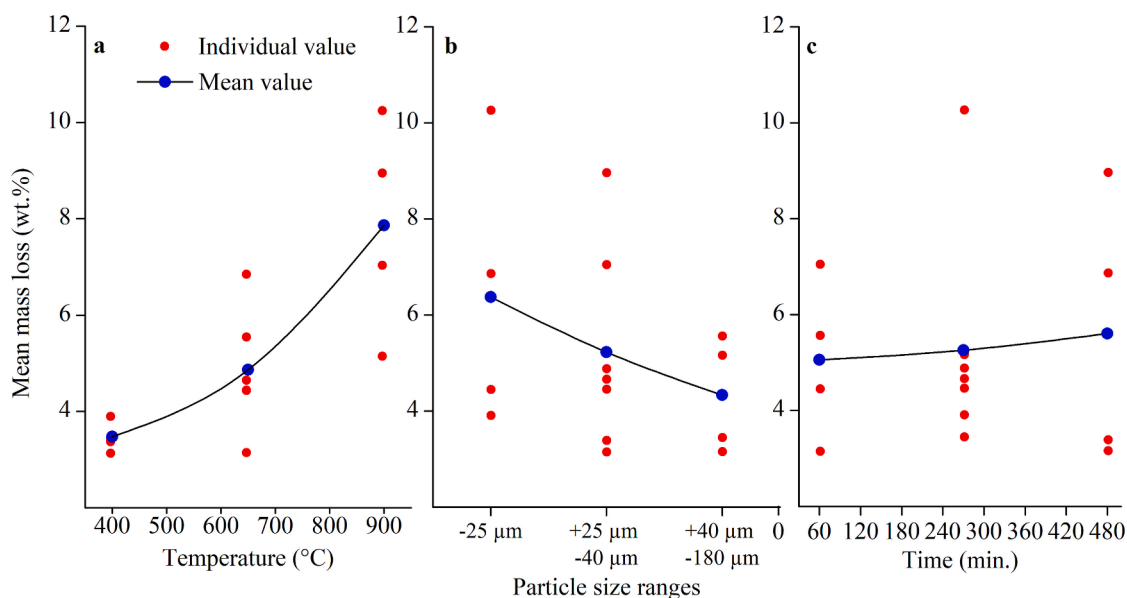


Fig. 2. Individual data points, and mean value analysis of a) temperature b) particle size ranges c) time.

Table 5
Regression equations.

Response	Regression Equations	R ²	P value
Mass loss (wt.%)	$5.87 + 3.551X_1 - 0.01066X_2 - 0.00565X_3 + 0.2X_1^2 + 0.000013X_2^2 + 0.000003X_3^2 - 0.00465X_1X_2 - 0.00574X_1X_3 + 0.000008X_2X_3$	96.86	0.003
Total LREE ext.(wt.%)	$1.8 - 17.1X_1 + 0.143X_2 + 0.1355X_3 + 0.5X_1^2 - 0.000107X_2^2 - 0.000148X_3^2 + 0.0258X_1X_2 - 0.005X_1X_3 - 0.000078X_2X_3$	55.64	0.700
Ce Ext. (wt.%)	$-36.9 - 48.2X_1 + 0.318X_2 + 0.178X_3 - 0.95X_1^2 - 0.000267X_2^2 - 0.000131X_3^2 + 0.077X_1X_2 + 0.0006X_1X_3 - 0.000153X_2X_3$	77.67	0.242
La Ext. (wt.%)	$27 + 4.1X_1 + 0.0286X_2 + 0.1139X_3 + 0.66X_1^2 + 0.000X_2^2 - 0.000172X_3^2 - 0.0094X_1X_2 - 0.009X_1X_3 - 0.00003X_2X_3$	68.04	0.449
Nd Ext. (wt.%)	$32.5 + 7.2X_1 + 0.0074X_2 + 0.696X_3 + 5.01X_1^2 + 0.000013X_2^2 - 0.000101X_3^2 - 0.009X_1X_2 - 0.0137X_1X_3 - 0.00002X_2X_3$	65.99	0.494
Pr Ext. (wt.%)	$38.7 + 6.3X_1 + 0.0058X_2 + 0.0308X_3 + 5.64X_1^2 + 0.000012X_2^2 - 0.000061X_3^2 - 0.0111X_1X_2 - 0.0071X_1X_3 + 0.000005X_2X_3$	65.10	0.513
Sm Ext. (wt.%)	$30.6 + 6.7X_1 + 0.0008X_2 + 0.0519X_3 + 7.37X_1^2 + 0.000022X_2^2 - 0.000071X_3^2 - 0.0011X_1X_2 - 0.0183X_1X_3 - 0.00002X_2X_3$	68.44	0.441

calcined powder were compared in Fig. 3 just to understand whether bastnasite phase was transformed or not. The absence of main peaks of bastnasite phase in calcined sample indicated that even in the sample with lowest LREE extraction rate, bastnasite has been successfully calcined. Since calcination is based on phase transformation, it would be better to quantify the process from XRD patterns, but as seen from Fig. 3, it is quite challenging task to determine how much bastnasite is transformed by Rietveld analysis due to complex nature of the ore, and so that high number of overlapping peaks. Furthermore, leaching extraction values were taken as an experimental response to determine calcination parameters giving the highest efficient REE extraction value. In the

meantime, non-calcined ore (below 25 μm) was also leached with the same conditions applied to calcined sample, and total LREE efficiency was found to be 10.977 wt%.

R² value for total LREE extraction and p-value rate were 55.64 and 0.7, respectively. Other individual REE extraction R² and p-values can be found in Table 5. These values were quite different than the value for mass loss rate. The main reason for low R² value, and thus low predictability of the model is due to the complex nature of the ore, and different dissolution properties of each element. As can be seen clearly from the mean extraction efficiency versus temperature diagram for all LREE in Fig. 4, while all LREE mean extraction efficiencies increased

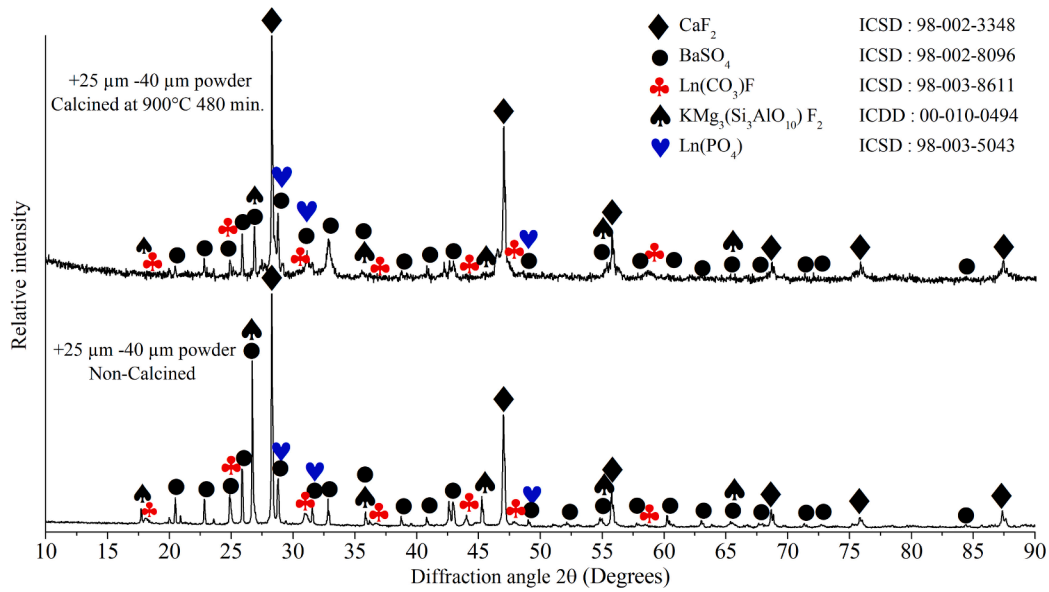


Fig. 3. XRD pattern of calcined, and non-calcined powder.

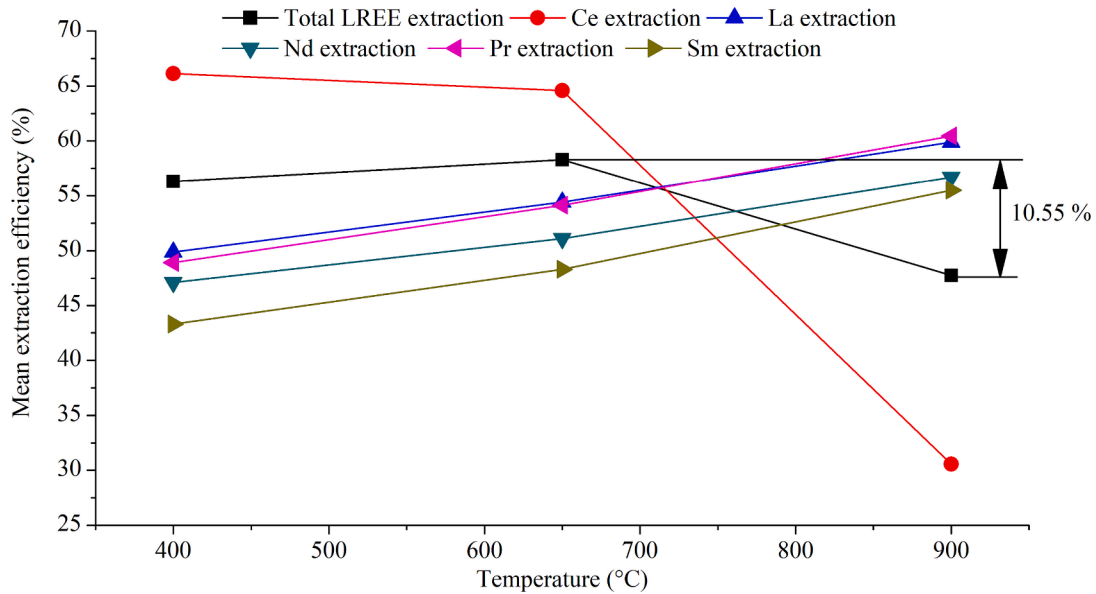


Fig. 4. Mean extraction efficiency versus temperature diagram.

with increasing temperature, Ce extraction efficiency dramatically dropped down at experiments conducted at 900 °C, and caused total LREE decrease in 10 wt%. This irregular, and different behavior of Ce clearly explained the reason for low R^2 value.

The reason why Ce showed opposite behavior to all other LREE was due to phase transformation of soluble 3 valance state Ce (Ce_2O_3) to insoluble 4 valance state Ce (CeO_2) (Allahkarami and Rezai, 2021). This transformation was detected by the phase analysis. In Fig. 5, XRD pattern of samples with highest, and lowest Ce extraction efficiency were compared. It is observed that CeO_2 phase peaks have started to appear in the lowest Ce extracted sample. According to this phenomenon, the efficiency of Ce extraction at all experiments conducted at 900 °C should be lower than others. However, data represented in Fig. 6 shows that mean Ce extraction value for experiments conducted at 900 °C, and with coarser particles (+40 μm –180 μm) was higher than experiments conducted at other temperatures. Once individual experiments (No:13, and 14) conducted at 900 °C were checked, it could be

interpreted that having larger particle size restricted complete phase transformation from Ce_2O_3 to CeO_2 , and consequently increased Ce extraction efficiency opposite to findings at smaller particle size. From grain size interaction versus temperature plot given in Fig. 6, it was also understood that decreasing particle size from below 180 μm to below 40 μm increased Ce extraction around 10 % but further decrease below 40 μm did not result a considerable influence on mean extraction efficiency at 400, and 650 °C. However, for experiments conducted at 900 °C, Ce extraction decreases with increasing particle size due to kinetic effects. These findings claimed that grain size, and temperature play a critical role about phase transformation, and consequently LREE extraction efficiency. Another factor that influences reaction kinetics is calcination duration. Upon analyzing the results of experiments 1 and 4 conducted at 400 °C, and experiments 5, and 10 conducted at 650 °C, it was observed that increasing the calcination duration from 60 min to 480 min led to an increase in extraction efficiencies between 5 wt% to 10 wt %. But this increase was not valid for the experiments conducted at

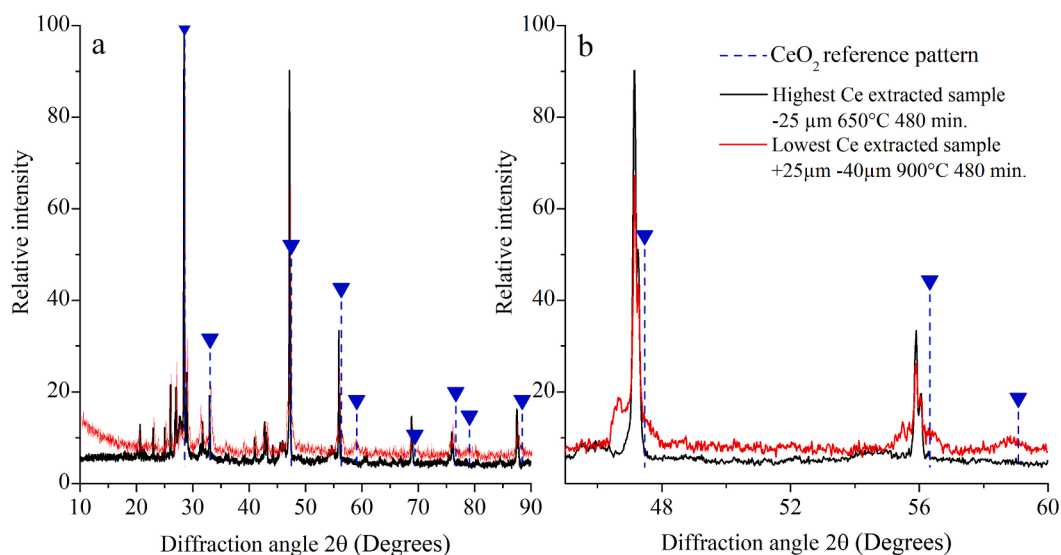


Fig. 5. a) Comparison of xrd patterns between the highest, and the lowest Ce extracted samples b) enlarged view to CeO₂ peaks concentrated area in the pattern.

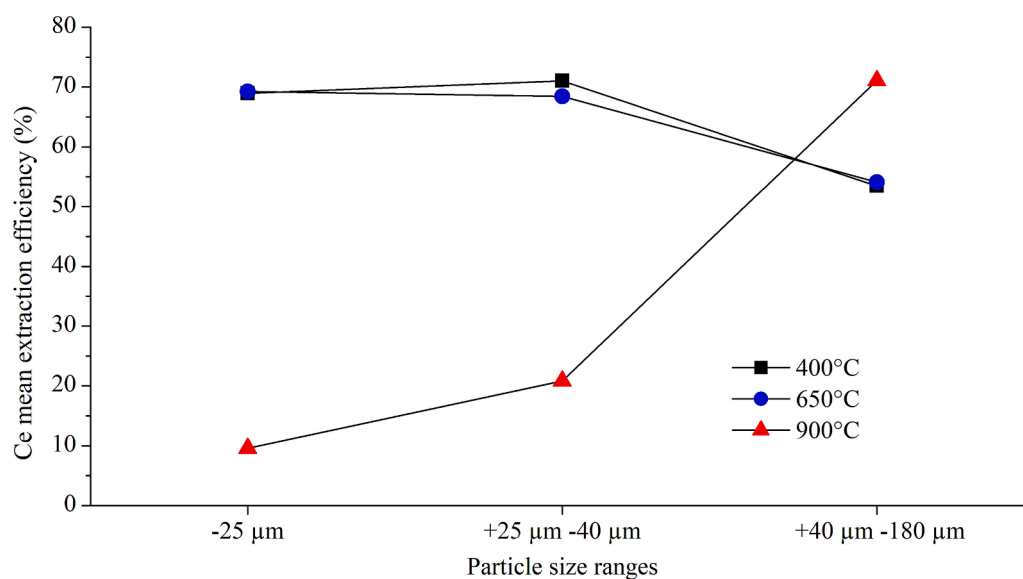


Fig. 6. Interaction plot for Ce.

900 °C because of the change in Ce valance as explained above. Consequently, time was determined to be another critical factor for phase transformation, but less efficient than temperature, and grain size.

3.3. Model control experiments for highest extraction efficiency

The main effect plots were analyzed in order to determine the calcination parameters that yields the highest extraction efficiency. While working on it, Ce extraction values were taken as a reference due to its high impact on total extraction efficiency. In the previous part of the study, it was understood that temperature was more crucial for determining highest efficiency parameters than duration and particle size. For that reason, calcination time was set around to.

middle as 180 min, and particle size was kept to the lowest as below 25 μm which contains highest LREE within 3 particle size ranges used in the study. Subsequently, three different temperatures in close proximity to the highest extraction value were selected for model control experiments while other parameters taken as constant. These temperatures are highlighted in Fig. 7 as 500 °C, 600 °C, 700 °C, and extraction results for

the experiments conducted at these temperatures were given in Table 6. The highest total LREE extraction was found to be 73.773 wt% in the experiment conducted at 500 °C. For other temperatures, LREE extraction efficiency was in a decreasing trend. Ce extraction efficiency declined around 17 wt% from 500 °C to 700 °C as observed in model experiments. Two more identical experiments at 500 °C were conducted, and mean LREE extraction efficiency of triplicated experiment was found to be 75.986 wt%. Individual LREE extraction efficiency data was given in Table 7. In this table, calculated extraction value by the formulas given in Table 5 is also illustrated. It is seen that there was 10 percentage difference between measured, and the predicted value which can be accepted as good estimate once complex nature of the ore is taken into account. As a conclusion, calcination temperature of Eskisehir bastnasite ore was found to be 500 °C which is in a good agreement with literature (García et al., 2021). Moreover, in this study, different from literature, optimum temperature was found by leaching calcines in a green DES media.

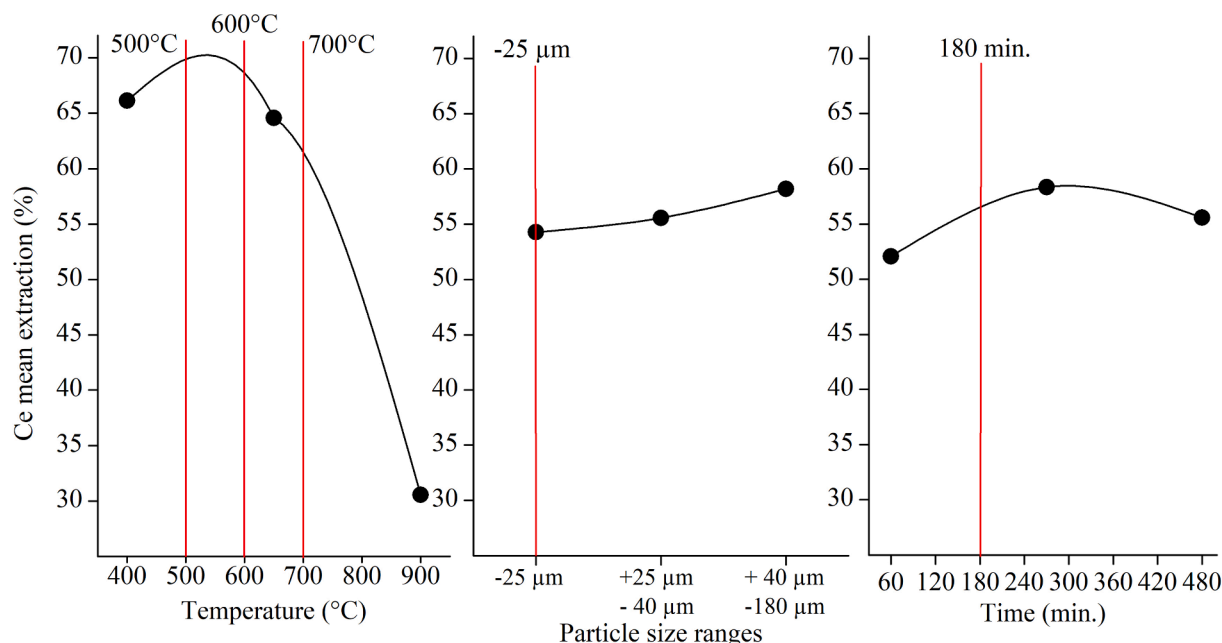


Fig. 7. Mean extraction efficiency plot showing the set parameters for control experiments.

Table 6
Control experiments' results for Light Rare Earth Element (LREE).

Temperature (°C)	Extraction (wt. %)					
	La	Ce	Pr	Nd	Sm	Total LREE
500	64.149	86.648	71.943	65.996	50.615	73.773
600	63.538	70.086	62.485	59.738	46.061	65.951
700	59.393	69.703	59.722	59.164	40.040	63.496

Table 7
Repeated experiments' results conducted at the highest efficiency conditions for Light Rare Earth Element (LREE) efficiency.

No of trials	Extraction (wt. %)					
	La	Ce	Pr	Nd	Sm	Total LREE
1st trial	64.149	86.648	71.943	65.996	50.615	73.773
2nd trial	65.495	87.395	73.115	66.976	51.346	74.841
3rd trial	69.706	92.886	78.627	66.544	56.663	79.345
Median value	66.450	88.976	74.562	66.505	52.875	75.986
Calculated value	56.251	77.895	54.876	51.690	46.376	64.776

4. Conclusion

Calcination parameters' influence on leaching yield of bastnasite ore from Eskişehir province was reported for the first time in literature. In addition to that, the ore was successfully leached with a green leaching media to understand calcination efficiency. The ore was subjected to calcination at different temperatures, duration, and particle size ranges in the current study, and experiment setup was modelled according to response surface methodology. All calcined samples were leached at identical conditions with DES to understand the calcination parameters influence on extraction efficiency. The highest LREE extraction was found to be 75.986 wt% for the sample calcined at 500 °C during 180 min. and with particles finer than 25 μm. The same experiment was triplicated, and found an acceptable deviation once complex nature of the ore was taken into account. Also, calculated leaching efficiency from regression analysis was close enough (around %10 difference) to real

leaching efficiency. Ce phase transformation from soluble (Ce_2O_3) to insoluble form (CeO_2) was proved by XRD analysis. This transformation has dropped Ce leaching value from around 80 % (Experiment No:10) to around 10 % (Experiment No:13). Furthermore, the most effective parameter was determined as temperature. Besides, due to low phase transformation kinetics of large particles, experiment with coarser particle size ranges conducted at 900 °C has resulted high extraction efficiency (71.061 wt%) similar to experiments conducted at 400 °C (74.1 wt%). Calcination duration was not as effective as temperature, and particle size ranges. In conclusion, calcination conditions for bastnasite ore giving the highest extraction efficiency were developed by leaching the calcines in an environmentally friendly leaching method. Also, the first step of whole new REE extraction process was developed in this study.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used scite.ai website in order to increase the readability of introduction part. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

S. Samet Kaplan: Writing – original draft, Investigation, Formal-analysis. **Cisem Celik Kurtulan:** Writing – original draft, Methodology. **Sebahattin Gurmen:** Writing – review & editing. **Gokhan Orhan:** Writing – review & editing. **M.Seref Sonmez:** Writing – review & editing, Supervision.

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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Data availability

Data will be made available on request.

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