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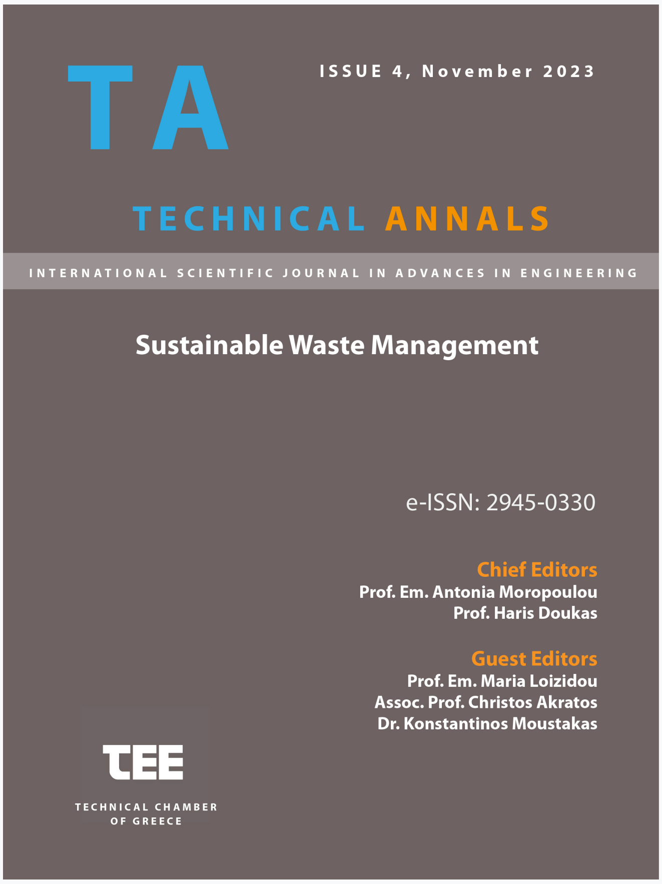

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Sustainability analysis for scandium recovery from secondary sources

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Abstract. Primary aluminium industry is one of the largest industries associated with high greenhouse gas emissions. It is reported that in 2022, the aluminium production emitted nearly 270 Mt of direct CO_2 in the atmosphere. To achieve the European goals of zero emissions by 2050, a reduction of 4 % annually is essential. The industry needs to take a turn towards less impactful production practices, focusing on the valorisation of residues for promoting sustainability. Bauxite residue from alumina production represents a remarkable source of Rare Earth Elements (REEs). This study offers valuable insights into the environmental and economic aspects of processes related to resource Scandium (Sc) extraction and processing in Greece, Romania and Turkey. In this frame, a comparative analysis of the environmental impact of the extraction process of REEs from Bauxite Residues (BR) in the regions mentioned above is presented. The results show that an up to 23 % greenhouse gas emissions reduction can be achieved, while the environmental categories of human health risks, aquatic toxicity potential, and terrestrial ecotoxicity potential are improved by applying hydrothermal processes and direct leaching to BR. While the stages of Sc extraction remain consistent, variations in the chemical compositions of BR underscore the influence of local factors. The findings also emphasize the importance of tailoring extraction processes to local conditions and compositions for scandium extraction. These insights can guide industry decisions and contribute to responsible resource management in the future.

Keywords: Extraction of Scandium; Bauxite Residue (BR); Rare Earth Elements (REEs); Life Cycle Assessment (LCA); Aluminum refineries; Circularity

1 Introduction

The primary aluminum industry is a high energy intensive industry, responsible for more than 3 % of total global emissions [1]. Following the electricity and steel industries, primary aluminum industry is the third largest source of greenhouse gas emissions. It is reported that in 2022, the aluminium production emitted nearly 270 Mt of direct CO2 in the atmosphere [2]. According to the International Aluminium Institute, the annual production of aluminum was 69 million tons in 2022, with China being the world-leading producer accounting for 57 % of the global production [1]. However, in order to achieve the transition towards a climate-neutral economy by 2050, the global direct emissions from aluminium production should decline at nearly 4 % per year up to 2030 [3]. In this scope, the aluminium industry needs to explore and apply near zero emissions technologies to reduce emissions from both primary and secondary aluminium production as well as to increase scrap collection and recycling [3]. To realize the scale and resource-intensive nature of primary aluminium production, it is essential to understand the significant quantities of bauxite required. To produce 1 ton of aluminium, 4-5 tons of bauxite are required [4]. Firstly, the mining of raw ore takes place and is followed by the extraction of metal through a series of long-established and vertically integrated industrial processes [5].

Bauxite residue (BR) is a waste product of the alumina refining in the Bayer process. Historically, BR was often stored in large impoundment areas, which could lead to environmental impacts due to the risk of dam failures and environmental contamination. Currently, there are four major disposal routes, which include the marine and slurry disposal, dry stacking, and dry cake stacking. Since the 1980s, there has been a shift away from lagoon-type disposal towards dry stacking, as this method can reduce the potential for leakage, while also reducing space required for storage and improving the recoveries of soda and alumina. Marine disposal does not require land storage, but may result in the release of hazardous metals into the marine environment, which can increase seawater turbidity due to residue dispersion and formation of colloidal compounds [6], [7]. Dry stacking is widely used for BR disposal at large alumina refineries, as it is able to reduce the potential for the caustic liquor leakage into the surrounding environment, to minimize the required land area, and maximize the recoveries of soda and aluminium. In the dry stacking method, the residue slurry is thickened to 48–55% solids and then deposited in layers on a sloping surface, allowing rainwater to run off. This method leads to minimizing the liquid stored in the disposal area, lowering the risk of leakage, and improving structural integrity of the disposal site [8].

However, stockpiling of materials with such a large volume bares environmental risks, thus valorizing bauxite residue is essential. The exploitation of BR will not only benefit the environment but also serve as a source of valuable metals. It is reported that BR contains significant concentrations of critical metals [9], such as aluminium, iron, titanium, as well as some Rare Earth Elements (REEs). Among them scandium (Sc) has the most economic value, accounting for more than 90 % of the total value, due to its difficulties associated with its extraction and purification [10]. Because of its widespread availability, BR is considered a promising secondary resource for valuable metals [10].

Rare earth elements are Critical Raw Materials (CRMs) that have gained attention over the last few years thus, the demand for these elements is continuously growing. A shift towards a sustainable economy can be achieved because they could be applied in clean energy technologies, thus reducing our reliance on fossil sources. However, their production, their supply chain, for instance, the geological characteristics of a mineral deposit, mineral type and composition, and the methods of extraction lead to environmental impacts [11]. As a REE, Sc has attracted the interest of researchers in the recent years due to its high value. Its unique physical and chemical properties make it suitable for applications in solid oxide fuel cells (SOFC's) and in high-strength aluminium alloys as well as in many advanced manufacturing industries [12]. Because of its various applications and limited supply, Sc is considered to be a critical raw material [13]. The global supply and consumption of Sc is approximately 10 to 25 tons per year. China is the largest producer of Sc (66 % of global Sc production) followed by Russia (26 %) which has been the second significant supplier to global markets, especially Europe, and Ukraine (7 %) [14]. As for the extraction of Sc, in nature it can be found only in small volumes thus, the industrial mining for primary extraction is unaffordable. Currently, Sc is mainly produced as a by-product during the processing of various ores or it is recovered from previously processed tailings or residues, such as BR [10], [15].

The chemical composition of BR varies and depends on the origin of the bauxite ore and the operating conditions during the Bayer process [10]. A typical BR material contains 5-60 % iron oxide (Fe_2O_3), 5-30 % aluminium oxide (Al_2O_3), 0.3-15 % titanium dioxide (TiO_2), 2-14 % calcium oxide (CaO), 3-50 % silicon dioxide (SiO_2) and 1-10 % Na_2O [16]. Also, traces of arsenic, beryllium, cadmium, chromium, copper, gallium, lead, manganese, mercury, nickel, potassium, thorium, uranium, vanadium, zinc, and a wide range of rare earth elements can be found in BR. Certain components do not dissolve during the Bayer process, remaining as part of the BR. Others dissolve in the Bayer process solution, where they either accumulate within the solution, precipitate in the residue, or form aluminum hydroxide in the final product. The extent to which elements are extracted into the solution or transformed in the bauxite residue depends on the processing conditions [16]. Iron oxides, mainly in the form of hematite in BR, represent almost half of the BR mass, therefore their effective separation can increase the basic metal and REEs content in the residue by 60-70 %. This can be achieved with the hydrothermal transformation of the poorly magnetic hematite to high magnetic susceptibility magnetite and apply magnetic separation to the formed magnetite residue. Prior experimental evidence has shown that the conversion of hematite to magnetite can be achieved during the Bayer process with the addition of $FeSO_4$ or 2 % iron powder in the Bayer liquor. The magnetite transformation exceeded 80 % of all the iron-bearing minerals in BR after 40 min of digestion, which was amenable to recovery of the iron minerals in a weak magnetic field. The conversion of hematite to magnetite in BR, followed by the recovery of basic metals and REEs from the non-magnetic fraction, is a highly attractive BR valorisation option.

In this frame, two main processes are studied, hydrothermal transformation and direct leaching. Hydrothermal transformation aims to convert the hematite found in BR into magnetite through hydrothermal processes and subsequently separating this magnetite from BR using magnetic methods. This process offers the potential to create a concentrated mixture of basic metals and REEs from BR, which can then undergo direct leaching. Additionally, this process yields a high-iron magnetic fraction that has diverse applications, such as in pigments and ceramics. This innovative method represents a new and valuable approach to recovering metal values from BR and making productive use of the resulting residue. Then direct leaching takes place and higher acid concentrations, exceeding 3M along with elevated solid-to-liquid (S/L) ratios are utilized in order to avoid silica dissolution. In addition, high S/L ratios, greater than the conventional 5 % S/L ratio are utilized to enhance the concentration of REEs and Sc in the leaching solution.

The scope of this study is the environmental assessment of the extraction of REE from BR in three regions, Greece, Romania and Turkey. As for the capacity production in each refinery the Aluminium of Greece (AoG) facility has a yearly production capacity of more than 190,000 tons of aluminium and 860,000 tons of alumina being the largest vertical producer of aluminium and alumina in the EU [17]. Alum Tulcea stands as the exclusive alumina refinery in Romania, with a production capacity of 600,000 tons per year [18]. The ETI Aluminium plant in Turkey, also known as the Seydişehir Aluminium Plant, occupies an impressive indoor area of approximately 12,000,000 square meters, making it the largest modern aluminium manufacturing facility in the country. In terms of production, it holds an annual capacity of 120,243 tons of round ingots and 80,000 tons of primary aluminium [19].

The study is based on the environmental and economic impact of efficient processing of the remaining BR residue to achieve maximum extraction and recovery of Sc and REEs as well as the production of a marketable magnetite concentrate corresponding to about 35 % of the processed BR quantity. To this end, a Life Cycle Assessment (LCA) is performed, to analyse the environmental impacts from the treatment technology of BR of the above regions. A life cycle impact assessment (LCIA) was completed using the Grave-to-Cradle model, and the following environmental impact categories were reported: global warming potential, abiotic depletion potential, freshwater aquatic ecotoxicity potential, human toxicity potential and terrestrial ecotoxicity potential. The results of this research emphasize the importance of generating reliable data for increasing application of LCA as a proven tool for sustainable development, supporting decisions for the industrial sector.

2 Materials and methods

2.1 LCA Methodology

To evaluate the environmental impact of the extraction of Sc in three different countries, an LCA was performed, following the standardized procedures described by ISO 14040:2006 and 14044:2006/A1:2018 [20], [21] and the International Life Cycle Data (ILCD) Handbook [22]. The LCA framework consists of: (1) the goal and scope definition; (2) the Life Cycle Inventory (LCI) preparation; (3) the Life Cycle Impact Assessment (LCIA); and (4) the interpretation of the results. The LCA was conducted with the commercial software package, Sphera LCA FE database. The calculation of the impacts was based on the CML (Centrum voor Milieukunde Leiden) 2001 standard developed by the Centre of Environmental Science of Leiden University.

2.2 Goals, Scope and Functional unit

The primary objective of this LCA study is to conduct a comprehensive assessment of the environmental potential of end-of-life processes for Sc extraction, achieved through innovative leaching and recovery treatments. Furthermore, it seeks to identify hot spots, optimize processes, and provide a quantified assessment of the environmental impacts of the new technologies and final materials in comparison with conventional scenarios. The scope of this study is the end-of-life management and treatment of BR. The functional unit (FU) was the treatment of 1 ton of BR feed.

2.3 Scenario Description and System Boundaries

A " Grave-to-Cradle " analysis was conducted to assess the scandium extraction from bauxite residue in three different cases. The first case is associated with the AoG plant in Greece, the second with the Alum Tulcea in Romania and the third case refers to ETI Aluminium plant in Turkey. Each scenario includes the following four stages for Sc extraction process as well as for the separation of iron oxide as a product Fig. ***1***.

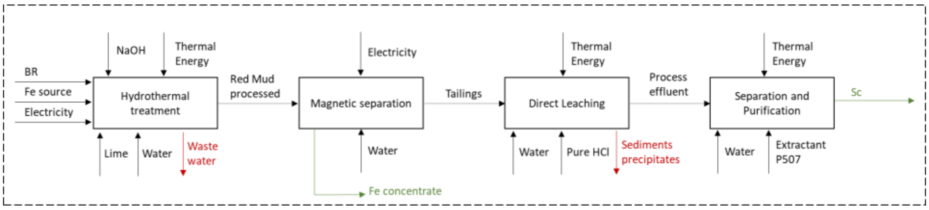

Fig. 1. System boundaries of the LCA scenario

Stage 1: Hydrothermal Treatment

In the initial stage of the process, hydrothermal treatment operations are carried out. The primary inputs include BR, which has undergone bauxite digestion and drying for a cleaner by-product, lime, water (deionized), iron sulphate, and sodium hydroxide. These materials are then hydrothermally treated and as a consequence hydrated alumina is generated. The process occurs at high temperature (250 °C), 480 psi pressure and at rotation speed of 400 rpm for 180 minutes. As a result, the output BR undergoes a substantial reduction in impurities, which increases the Fe2O3 content.

Given that the BR is a highly alkaline (pH = 10–12.5) by-product and the addition of the sodium hydroxide to the hydrothermal treatment operations, the generation of an alkaline waste water is inevitable. This stage serves as a crucial preparatory step to make the raw material compliant to further processing.

Stage 2: Magnetic Separation & Drying

The next stage involves wet magnetic separation and drying processes. At this process, the input consists primarily of processed red mud and water, as well as electricity, associated with the use of a magnetic drum separator. Regarding the output products, it is noted that Fe concentrate contains a higher percentage of Fe2O3 compared to the input and in a larger volume in comparison with the tailings, indicating the successful removal of other minerals through magnetic separation.. Through the application of magnetic separation and subsequent drying, the materials are separated into two distinct products: a concentrated iron (Fe) product (iron oxide) and residual tailings, which will be further processed in the next stage.

Stage 3: Direct Leaching

In the third stage, known as direct leaching, the tailings from the previous stage are further processed. The feed at this stage includes the tailings, pure hydrochloric acid (HCl) and water. The leaching process is conducted in leaching glass reactors of 1L for 60 minutes at a temperature of 120°C, with a rotation speed of 500 rpm. As a result, it is obtained as a product an aqueous solution containing up to 85 % Sc and various other elements and solid residues (sediments precipitates), which are considered as a by-product.

Stage 4: Separation and Purification

The final stage of the Sc extraction process involves separation and purification. The objective in this stage is to purify Sc from the input materials. Thus, solvent extraction process is applied, in which Sc transfers from one solvent to another owing to the difference in solubility. The solvent extractant reagent used in the procedure is P507. Water and thermal energy source are also added.

2.4 Assumption and Limitations

Prior to the LCA modelling, main assumptions and limitations were clarified in order facilitate the procedure. The main assumptions/limitations are presented below:

- Industrial-scale treatment may not reflect the actual conditions of smaller-scale or pilot-scale operations, which can have significantly different environmental impacts. It is crucial to consider how the scale of the operation might influence resource consumption, energy use, and emissions.
- The geographical characteristics can greatly impact the environmental performance of the BR treatment process. This analysis focuses on the specific geographic location of the refineries and is being aware that the results may not be readily transferable to different locations due to varying conditions.
- Transportation can be a significant contributor to the overall carbon footprint, especially for plants located far from the source of raw materials. Although for this analysis the transportation of materials to plant and of the intermediate products inside the plant are not considered.
- While this analysis assumes a consistent process efficiency level, it acknowledges that in reality, processes can experience variability due to equipment performance or optimization efforts. Recognizing this limitation is essential for understanding the potential dynamic nature of the environmental impact.

2.5 Life Cycle Impact Analysis

In this LCA study five impact categories are examined, which were selected according to the scope of the study, as well as to comply with ISO 14040 and 14044 standards containing the broadest set of midpoint categories. The impact categories are summarized in Table 1.

The CML 2001 standard is a method for evaluating the environmental consequences of a product or process throughout its entire life cycle. It was developed by the Center of Environmental Science of Leiden University and was published in a guide to the ISO standards in 2001 [23].

Table 1. LCIA impact categories

Impact Category	Selected Indicator	Unit
Climate Change	Global Warming Potential (GWP) (CML 2001)	kg CO_2 eq
Abiotic depletion	Abiotic Depletion Potential (ADP) (CML 2001)	kg Sb eq
Freshwater Aquatic Ecotoxicity	Freshwater Aquatic Ecotoxicity Potential (FAETP) (CML 2001)	kg DCB eq
Human Toxicity	Human Toxicity Potential (HTP) (CML 2001)	kg DCB eq
Terrestrial Ecotoxicity	Terrestrial Ecotoxicity Potential (TETP)	kg DCB eq

3 Life Cycle Inventory

Life Cycle Inventory (LCI) refers to all the inputs and outputs data of the system, consisting of material flows, energy and emissions. To ensure the credibility of the data, the processes provided by the Sphera database were used. The quantities of material and energy flows for the production processes are obtained from laboratory analysis.

The chemical composition of BR differs in each scenario due to its origin; thus, Table 2 derives from material characterization results. The output product of the second stage, Fe concentrate, contains a higher percentage of Fe2O3 than the initial concentration in BR. In the first case (GR), the concentration of Fe2O3 has been increased from 45.58 % to 56.35 %, in the second case (RO) from 39.18 % to 62.56 % and in the last case (TR) from 35.25 % to 40.04 % respectively. That increase indicates that the hydrothermal treatment process was successful and the impurities have been reduced compared to the feed.

Table 2. Chemical composition of BR

BR Composition	Case 1 - GR (%)	Case 2 - RO (%)	Case 3 - TR (%)
Fe_2O_3	45.58	39.18	35.25
Al_2O_3	15.32	17.37	17.52
CaO	9.19	4.88	4.84
TiO_2	5.70	2.20	4.62
Cr_2O_3	0.24	0.10	0.09
Na_2O	1.76	6.71	6.98
SiO_2	9.72	11.53	14.63
P_2O_5	0.25	0.32	0.15
SO_3	0.89	1.04	0.74
V_2O_5	0.17	0.14	0.07
MgO	0.46	0.02	0.18
LOI	10.26	16.27	14.12

The LCI data for Case 1 (GR), Case 2 (RO) and Case 3 (TR) are summarized in Table 3, Table 4, Table 5 respectively. Although the process and the reagents are common in all cases, the input flow differs, due to the different chemical composition of BR. In all cases, the reagents usually come from a common supplier, while the energy supply depends on the location of the plant. Thermal energy is provided to the system in the form of NG, HFO, LFO and energy consumption is estimated in MJ. In Case 1 (GR), 4,726.83 MJ thermal energy is required, and is deriving from Greece's electricity grid mix. Fossil fuels have the biggest share in Greece's energy supply. The required thermal energy in Case 2 (RO) accounts for 4,726.7 MJ and is provided by the energy grid mix, which is composed mainly of hydrocarbons and coal. In Case 3 (TR) 5,798 MJ thermal energy is required and is provided by Turkey's electricity grid mix. Fossil fuels, including coal, natural gas, and oil, account for the majority of the energy supply.

Table 3. LCI data for Case 1, AoG plant (GR)

Flow	**Quantity**	**Unit**
Inputs		
BR	1,000.00	kg
Fe Source	576.00	kg
NaOH	23.50	kg
Water	37.62	m^3
Electricity	318.80	MJ
LFO	131.40	MJ
NG	2,441.43	MJ
HFO	2,154.00	MJ
Lime	30.30	kg
Pure HCl acid	95.40	kg
Extractant P507	2.37	kg
Outputs		
Waste water	1,681.00	L
Fe concentrate	541.00	kg
Sediments Precipitates	81.50	kg
Sc	0.16	kg

Table 4. LCI data for Case 2, Alum Tulcea plant (RO)

Flow	Quantity	Unit
Inputs		
BR	1,000.00	kg
Fe Source	560.00	kg
NaOH	23.50	kg
Water	37.53	m^3
Electricity	318.80	MJ
LFO	90.20	MJ
NG	4,404.00	MJ
HFO	232.50	MJ
Lime	30.30	kg
Pure HCl acid	94.70	kg
Extractant P507	2.36	kg
Outputs		
Waste water	1,681.00	L
Fe concentrate	558.00	kg
Sediments Precipitates	81.50	kg
Sc	0.16	kg

Table 5. LCI data for Case 3, ETI Aluminium plant (TR)

Flow	Quantity	Unit
Inputs		
BR	1,000.00	kg
Fe Source	386.00	kg
NaOH	23.50	kg
Water	37.83	m^3
Electricity	318.80	MJ
LFO	191.70	MJ
NG	2,451.30	MJ
HFO	3,155.00	MJ
Lime	30.30	kg
Pure HCl acid	138.00	kg
Extractant P507	3.46	kg
Outputs		
Waste water	1,681.00	L
Fe concentrate	464.00	kg
Sediments Precipitates	117.16	kg
Sc	0.23	kg

4 Results

The LCIA results for the different scenarios are shown in Table 6 and in Figure 2. The results showed the environmental impact associated with the Sc and Iron recovery processes in Greece, Romania and Turkey. The analysis considered both the efficiency of the processes proposed as well as the energy contribution related to geographical conditions.

In terms of GWP, Case 1 (GR) has a total of 722.72 kg CO_2 eq, which is approximately 82.50 kg CO_2 eq lower compared to Case 3 (TR), while Case 2 (RO) has an even lower GWP of 619.91 kg CO_2 eq. These differences reflected in percentages are respectively 10.2 % and 23 %, for Case 1 (GR) and Case 2 (RO), lower, compared to Case 3 (TR). According to the contributing processes the hydrothermal treatment is the main process responsible for the environmental impacts, accounting for approximately 54.7 % in AoG scenario, 55.6 % in ALUM, while in the ETI scenario, separation and purification process is the main contributor (44.9 %). Direct leaching and magnetic separation, on the other hand, each account for less than 10 % of the total GWP, emphasizing their relatively lower impact on global warming potential.

Considering ADP, Case 1 (GR) shows the lowest overall ADP, with a total of 0.000886 kg Sb eq. It is followed closely by Case 2 (RO), which exhibits a slightly higher ADP value of 0.000887 kg Sb eq, while, Case 3 (TR) stands out with the highest ADP value of 0.000923 kg Sb eq, suggesting a potentially more significant impact on abiotic resource depletion. Therefore, both Case 1 (GR) and Case 2 (RO) have lower ADP percentages compared to Case 3 (TR), with decreases of about 4 % and 3.9 %, respectively. In all cases, the magnetic separation process consistently stands out as the most significant contributor to the overall ADP of each plant, comprising 47.2 % in AoG and ALUM plants and 45.3 % in ETI, of the total ADP. Following closely behind is the hydrothermal treatment process, while the separation and purification stages have a minimal impact less than 1 % in all cases.

When it comes to Freshwater Aquatic Ecotoxicity, Case 3 (TR) has the highest total FAETP of 5.6 kg DCB eq, suggesting the highest potential impact on FAETP, while Case 1 (GR) follows with a total FAETP of 4.4 kg DCB eq Case 2 (RO) has the lowest total FAETP of 2.8 kg DCB eq and compared to Case 3 (TR) is substantially lower by 50.5 % approximately.

The separation and purification phase in the first Case (GR) accounts for 44.3 % of the total FAETP, followed by the hydrothermal treatment process (43.5 %). However, in the second Case (RO) hydrothermal treatment dominates with a contribution of 68.0 %, while the rest processes contribute to approximately 10 % each.

As for human toxicity it is obvious that Case 3 (TR) has the highest total HTP among the three cases, with a total of 113.1 kg DCB eq. Case 1 (GR) has a lower total HTP compared to Case 3, with a total of 43.9 kg DCB eq and Case 2 (RO) has the lowest HTP impact with the value of 25.2 kg DCB eq, exhibiting 77.7 % decrease compared to Case 3 (TR). In the first and in the third Scenario separation and purification stage is the main contributor, representing approximately 50.0 % and 75 % of the total HTP respectively, underscoring its potential impact on human toxicity. In the second Scenario hydrothermal pretreatment plays a crucial role contributing 55.6 % of the total HTP.

In terms of Terrestrial Ecotoxicity Potential Case 1 (GR) has a total of 2.01 kg DCB eq, which is by approximately 0.85 kg DCB eq lower compared to Case 3 (TR). Additionally, Case 2 (RO) has a total TETP of 1.43 kg DCB eq, indicating a decrease of approximately 50.3 % compared to Case 3 (TR). In Case 1 (GR) and Case 2 (RO) hydrothermal pretreatment dominates TETP, while in Case 3 (TR) separation and purification plays the most important role.

Table 6. LCIA results for all cases in terms of the selected indicators for impact categories

Indicators for impact categories	**Case 1 - GR**	**Case 2 - RO**	**Case 3 - TR**
GWP (kg CO_2 eq)	722.72	619.91	805.21
ADP (kg Sb eq)	0.000887	0.000887	0.000923
FAETP (kg DCB eq)	4.42	2.77	5.60
HTP (kg DCB eq)	43.90	25.19	113.10
TETP (kg DCB eq)	10.26	16.27	14.12

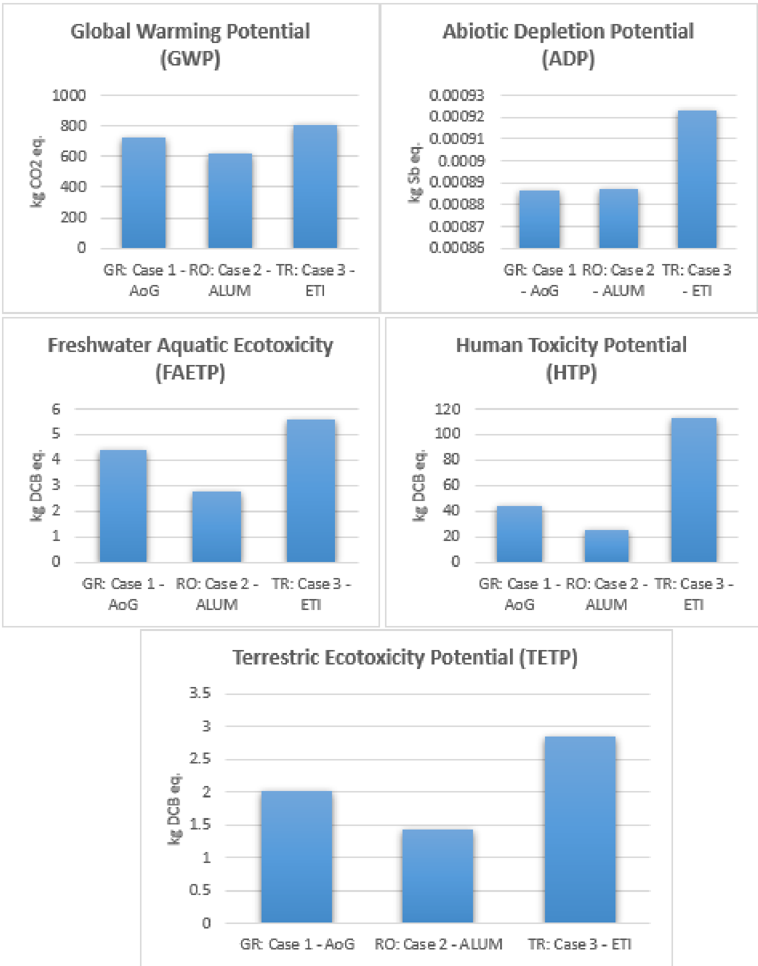

Fig. 2 LCIA results for all cases in terms of GWP, ADP, FAETP, HTP, TETP

5 Discussion

Proper handling of BR is a major challenge for the EU aluminium industry, raising concerns for the impact on both the environment and human health, as well as spatial limitations related to the sheer volume of residues. In 2019, the BR production in the EU was about 6.8 Mt/y [24]. The amount of stockpiled BR in the form of a dry matter was more than 250 Mt by the same year, raising concern for the availability of BR disposal space. The AoG refinery in Greece for example is responsible for 0.75 Mt dry BR production per year, requiring 1 km2 of land for its annual deposit. Alum in Romania accounts for 0.54 Mt and ETI in Turkey accounts for 0.44 Mt dry BR production [24].

In addition, landfilling is restricted by specific regulation for both non-hazardous and hazardous BR. According to the EU categorization of waste documentation [25], BR resulting from the alumina refining process is classified either as Non-Hazardous or Hazardous waste depending on the origin [26]. The classification can only be determined after the necessary test work has been undertaken [27]. If BR is considered non-hazardous, it is landfilled in accordance with the Directive 1999/31/EC, which mandates that non-hazardous waste must be disposed of in landfills, equipped with a natural or artificial geological barrier [26]. Additionally, these landfills should incorporate an artificial sealing liner above the geological barrier and a drainage layer at the top to ensure the protection of soil and water. Also, the same Directive indicates that the landfill regulations to the geological barrier can be limited when either the collection and treatment of leachate is not essential or it has been ascertained that the landfill has not potential hazard on the environment [26].

When BR contains hazardous substances, treatment of waste before its landfilling is required. The most appropriate treatment, including the stabilization of the organic fraction of waste, is applied, in order to reduce, as far as possible, the adverse effects of landfilling on the environment and on human health [28]. In addition, the Directive (EU) 2018/850, which is an amendment of the Directive 1999/31/EC on the landfill of waste, implies that as of 2030, all waste suitable for recycling or other recovery, shall not be accepted in a landfill with the exception of waste for which landfilling delivers the best environmental outcome [28].

According to research, disposal of BR in residual material landfill is one of the most hazardous approaches considering the radiological impact to biota for freshwater, marine and terrestrial ecosystems, due to prolonged release of radioactive substances [29]. Furthermore, landfilling may affect areas larger and distant from the actual deposits through deposition of fine dust particles, in particular in dry stacking. Therefore, soil is a valuable – yet often ignored – resource that needs protection, particularly for industrialized and more densely populated areas.

In contrast, utilization of BR can significantly reduce their impact while also producing valuable products such as construction materials. According to research, 1 kg of BR can be utilized for the production of 2.47 kg of bricks or 22.4 kg of cement, mixed of course with other raw materials. These approaches significantly minimize the impact in the ecosystem while not significantly affecting the impact on human health. In that sense, assessing the economic viability of these and other BR recycling approaches is essential to establish them as a valuable alternative to the outdated technique of landfilling.

As of now, economically efficient integrated technologies available for the total recycling of BR on a large industrial scale pose a challenge. However, the valorisation of BR contributes to the reduction of the management costs of RM. The cost for purchasing high purity Sc ranges from 4,219 € up to 4,876 € per 1 kg in the market [30]. Producing 1 kg Sc with the approaches analyzed above is estimated to cost 1,710 to 2,857 €, depending on the examined region. Although the process is common in all cases, the input of reagents differs according to the chemical composition of BR. In addition, thermal energy plays a significant role in the cost sharing and its price depends on the location of the plant, while each country has its own set price. The same applies with water and electricity, while the rest of the reagents usually come from a common supplier. According to the supplier, as well as the location of the supplier, the prices vary. Also, the amounts purchased, for instance if it is in wholesale or retail price, plays an important role. The purity of the reagent is a significant contributor to the price too, while as purity increases price rises accordingly.

The impact of landfilling and the potential of recycling gives ground to reopen the discussion on alternative sustainable pathways for BR handling in EU. The escalating production of BR, coupled with the limitations in disposal space, highlights the urgency for sustainable solutions. Transitioning from outdated landfilling methods to innovative recycling and valorization techniques mitigates ecological risks while presenting opportunities for creating value-added products like construction materials. Promoting research on these different approaches can establish their potential and benefits, incentivizing investments, fostering collaboration between industry stakeholders and regulatory bodies. This way, EU can advance towards a more sustainable and circular approach to BR management in line with its goal on sustainability and promoting the circular economy.

6 Conclusions

The novel extraction route analyzed in the study enables the extraction of Sc content from BR. To assess the overall environmental impact of the valorisation of BR, LCA is a powerful tool which can provide the most accurate results. The LCA conducted in this study investigates three different cases of Sc extraction through innovative BR treatment in Greece, Romania, and Turkey. The recovery of Sc was estimated up to 85%. The deviations between the three regions, highlights the adaptability and potential for improvement in these processes. While the stages of Sc extraction remain consistent, variations in the chemical compositions of BR underscore the influence of local factors. Turkey's red mud contains lower concentrations of Fe2O3, necessitating tailored treatment methods. This underscores the importance of considering local conditions and compositions when designing sustainable extraction processes.

The environmental impact assessments for the three cases reveal several findings. Scenario 2 (RO) consistently demonstrates the lowest environmental burdens and potential impacts across various environmental impact categories, such as GWP, FAETP, HTP, and TETP, indicating reduced greenhouse gas emissions, aquatic toxicity potential, human health risks, and terrestrial ecotoxicity potential accordingly. It is considered the most environmentally sustainable scenario because a 23% reduction in greenhouse gas emissions in comparison with the other cases can be achieved. Scenario 1 (GR) also shows reduced environmental impacts compared to Scenario 3 (TR) exhibiting 45 % lower ADP values and 61. 2 % lower HTP values compared to the third case. Important reductions were also reported in greenhouse gas emissions, indicating a 10.2 % reduction in GWP and a 21.1 % reduction in FAETP compared to case 3. Furthermore, the choice of extraction method significantly influences the environmental impact, with hydrothermal treatment process and separation and purification, playing the most important role in the majority of the environmental indicators.

It is expected that the environmental impacts may differ after full integration of the Sc production route in an aluminum plant and process optimization, while the reagents consumption can be reduced.

In conclusion, the necessity of exploring alternative, sustainable methods for managing BR becomes evident when considering the environmental impact of landfilling and the benefits of recycling. Moving from outdated landfill practices towards innovative recycling and valorisation approaches not only reduces ecological risks but also creates opportunities for the development of value-added products. These solutions will enable the EU to progress towards a more sustainable and circular approach to BR management, aligning with its goals of sustainability and the promotion of a circular economy.

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