Waste to Value – Sustainable Valorization of Bauxite Residue

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Abstract

Globally, the production of alumina generates approximately 175 million tonnes of bauxite residues (BR) per year, containing bulk metals such as aluminum (Al) and iron (Fe) as well as valuable critical metals such as Scandium (Sc), Rare-Earth Elements (REE), Titanium (Ti) and Gallium (Ga), which mainly accumulate in storage ponds. Currently, over 4 billion tonnes of BR have been accumulated worldwide. Due to limited storage space, stricter environmental regulations, and the growing demand for REEs, there is an urgent need for a sustainable approach to valorize these residues while minimizing waste volume. The industry is seeking a scalable and feasible solution to significantly reduce waste volume and extract metals for marketable off-takes. Many proposed routes have been studied, but they often lack economic viability or fail to reduce waste volume sufficiently, shifting environmental impacts to effluents or other difficult-to-manage waste.

INNORD proposes a multi-step process aimed at recovering bulk metals (Fe, Al, Na) and producing valuable metal concentrates (Sc/REE), achieving a volume reduction of over 85 %, and improving process economy by generating multiple marketable off-takes. The development objectives include a limited number of steps, extensive reagent recycling and minimizing regular effluent production. The process involves an alkalinity and DSP removal circuit, an iron conversion and recovery circuit, and a Sc/REE/TiO_2 extraction circuit.

This paper discusses the main steps of the proposed flowsheet, such as caustic recovery, DRI-grade iron production (DRI = Direct Reduced Iron), smelter grade alumina (SGA) production and critical metal concentrate generation. Additionally, experimental results from bench-scale testwork conducted on six different BR samples collected from alumina refineries worldwide are presented. The paper also reports on the main parameters influencing extraction steps and their impact on recoveries. Finally, a summary of technoeconomic assessment (TEA) and life cycle analysis (LCA) is provided for six BR feeds, discussing the impact of BR feed composition and off-take product selection on the TEA.

Keywords: Valorization, Waste volume reduction, Critical metals, DRI-grade iron, REE and Scandium.

1. Introduction

In the context of the battle against climate change, the demand for light metals such as aluminum is increasing, especially for the manufacturing of vehicles with lower fuel consumption. While this will result in decreasing greenhouse gas (GHG) emissions, aluminum production creates large amounts of waste. Aluminum smelters require pure alumina (aluminum oxide, Al_2O_3) for the Hall-Héroult process which consists of the electroreduction of the oxide to metal aluminum. Alumina is produced from bauxite ore via the Bayer process. During this process, the aluminum-containing minerals are dissolved in hot caustic soda (NaOH), and a slurry is produced that contains unreacted minerals, precipitated aluminosilicates (known as desilication products or DSP) and excess caustic soda solution. This slurry before filtration or pressing generally has a

solid content of 10–30 % which generates an alkaline residue with a pH value between 10–13. This waste is known as bauxite residue (BR) or "red mud". For every tonne of alumina, between 1 and 1.5 tonnes of BR are created. The global annual production is estimated at 150 to 300 million tonnes per annum (Mtpa). Annual production of alumina in 2020 was over 133 million tonnes resulting in the generation of over 175 million tonnes of BR, (Based on the statistics published by World-aluminium, the amount of BR is estimated using an average factor of 1.3 tonnes of BR per tonne of alumina produced) [1]. Currently, more than 95 % of this production is stockpiled, leading to over 4 billion tonnes accumulated globally to date.

In general, environmental issues associated with bauxite residue storage and disposal include its high pH (10–13), the potential for alkali (Na, K) and ecotoxic (V, As) metals seepage into groundwater, instability of storage and the impact of alkaline airborne dust on plant life. In several places, failure of storage pond dams has resulted in incidents in the past (Ajka, Hungary in 2010 and Barcarena, Brazil in 2018) which had significant environmental impacts on soil and water [2]. Various solutions have been developed to mitigate these issues such as neutralization of the causticity prior to storage and improved stacking techniques [3]. However, these solutions do not sufficiently reduce the volume of waste and do not prevent long-term groundwater contamination [4].

Moreover, BR is usually rich in iron, aluminum, titanium (Ti), as well as strategic and/or critical metals such as vanadium (V), scandium (Sc) and other rare-earth elements that are left unexploited. The value loss is estimated be up to 120 to 400 USD/tonne of BR based on the oxide content of dry BR, resulting in a loss of 21–70 billion USD per year worldwide.

The valorization of BR has been researched for decades, yet there is still no large-scale process in place to extract these metals and effectively reduce waste volume. One of the main challenges is achieving a significant waste volume reduction (> 70 %) in a way that is economically feasible. One potential solution is to extract bulk metals (such as Fe and Al) simultaneously with strategic metals (like Sc/REE and Ti) to increase potential revenue. It is crucial to consider capital and operating costs, as well as total energy consumption per tonne when evaluating economic viability.

Proposed methods for recovering multiple metals are often assessed based on the market price of commercial-grade metal oxides. However, this approach may complicate the process by making it difficult to meet market specifications and increase capital risks. It is essential to also consider the environmental impacts of any alternative solution to BR stockpiling. The goal should not be to create large amounts of effluent or additional solid waste that is even more challenging to manage. Creating such waste would delay the large-scale implementation of innovative processes due to additional regulatory constraints.

2. Innord Process

INNORD has developed a unique process to reduce the volume of BR by over 85 % through the recovery of bulk metals (Fe, Al, Na) and valuable metals concentrate (Sc/REE). The major reagents used in this process are recycled to minimize effluent generation. A simplified diagram for the proposed process is illustrated in Figure 1. The process developed by Innord addresses the sustainability challenge of BR accumulation and disposal in the following ways:

a) The volume reduction exceeds 85 %, saving significant storage space and allow for soil remediation work on BR-free areas, if accumulated tailings are processed.
b) The potential residues are amorphous silica with reduced causticity and toxicity compared to untreated BR. The pH is closer to 7 and the concentration of ecotoxic metals is lower.

c) The process is designed to minimize liquid effluents by internally recycling leaching solutions.
d) Direct greenhouse gas (GHG) emissions are minimized by utilizing the CO_2 emitted in the process for the precipitation of alkali-earth carbonates.

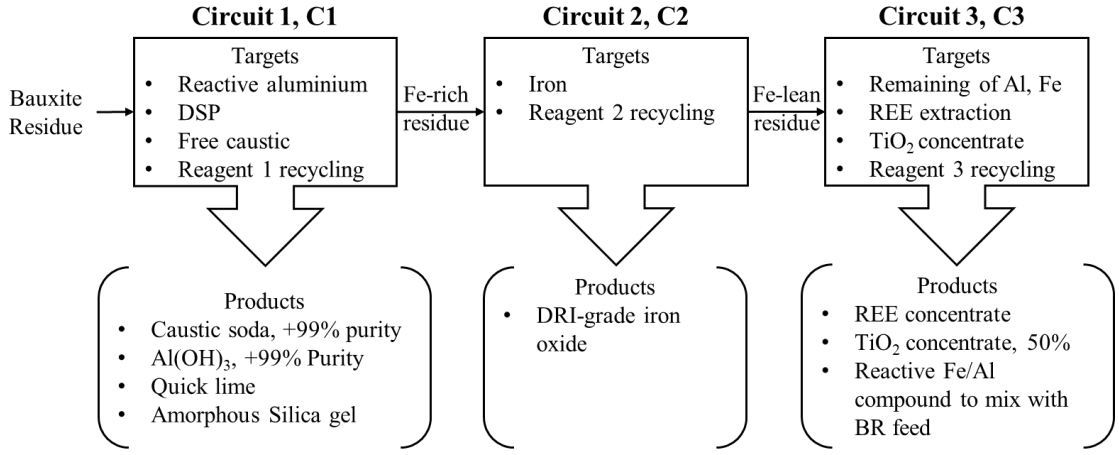

Figure 1. Process concept diagram for BR valorization.

The main steps of this process were applied at bench scale to six different BR samples collected from alumina refineries in five countries around the world. The samples were sourced from both legacy sites and fresh BR. The results were used as input into an Aspen process simulation to create a heat and mass balance. Subsequently, preliminary equipment selection, rating and sizing were conducted for each set of results for an identical process flowsheet. Finally, technoeconomic assessment (TEA) and life cycle assessment (LCA) studies were carried out to determine the profitability and sustainability performance of the proposed process.

3. Sample Preparation and Characterization

The collected BR samples were dried and ground to a particle size of less than 250 µm. The chemical composition of the samples was analyzed by X-ray fluorescence spectroscopy (XRF) for major elements, and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) for minor elements as presented in Table 1. Additionally, the moisture and loss on ignition (LOI) of all samples were measured at 100 °C for 20 hours and 1000 °C for 1 hour, respectively.

Table 1. Dry basis chemical composition of BR samples, wt.%.

Sample ID	S1	S2	S3	S4	S5	S6
Na_2O	7.2	11.5	11.6	4.7	2.9	10.1
CaO	7.1	6.1	5.7	1.8	1.48	12.6
Al_2O_3	17.7	21.6	23.6	18.5	15.9	26.9
SiO_2	7.6	17.6	16.8	8.6	5.9	21.2
Fe_2O_3	30.5	18.4	26.6	49.2	57.2	9.8
REO	0.09	0.02	0.12	0.04	0.01	0.14
Sc_2O_3	0.03	0.04	0.01	0.01	0.01	0.03
TiO_2	5.5	5.5	6.3	4.9	4.3	4
LOI@1000 °C	21	14.5	6.8	10	10.7	10.8
Sum	96.7	95.3	97.5	96.8	98.4	95.6
Moisture (%)	5.1	3.9	37.4	1	21.5	33

The variation in the source, type and composition of BR samples are essential for assessing the versatility of Innord's proposed process. In the present study, all the major steps were performed on all samples. However, there are minor steps that were conducted on selected sample and the results were extrapolated to the rest.

4. Methodology and Results

4.1 Alkalinity Removal, Circuit 1

Bauxite Residue was treated in two consecutive leaching steps using reagent 1 under atmospheric conditions. The first step occurred at approximately 95 °C while the second step took place at room temperature. The total elemental recoveries after the two steps are presented in Table 2.

Table 2. Recovery of elements after leaching steps (C1).

	Recovery, %					
Sample ID	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Na	99	98.6	98.9	94	100	100
Ca	96.6	58.7	36.1	77	85.2	35.7
Al	58.6	66	65.4	42	34.1	59.8
Si	70.3	85.3	82.1	53	51.6	72.9
Fe	0.2	0.8	0.1	0	0.1	2.9
Ti	0.2	3.5	0.8	1	0.5	4.1

It is indicated that among the major elements, Na was almost fully removed, and Al, Ca, and Si were partially removed from the residue and transferred to the next steps for recovery, while Fe, Ti, and a portion of Al, Ca, and Si remained in the solid phase and were collected as filtration cake. X-ray Diffraction (XRD) analysis showed that DSP phases disappeared during this step. Moreover, the recovery of Aluminum during this step depends on the amount of aluminosilicate minerals in each sample.

Table 3 shows the chemical composition of the iron-rich residue for each sample on a dry basis. Accordingly, mass reduction was reported for each sample ranging from 20 to 50 wt.%. The low mass reduction in S4 and S5 compared to the rest is attributed to having less caustic, calcium and silica in the BR feed to be removed during C1 treatment.

Table 3. Dry-basis chemical composition of iron-rich residue (C1 outlet to C2).

	Neutralization cake composition, wt.%					
Sample ID	**S1**	**S2**	**S3***	**S4**	**S5**	**S6***
Na_2O	0.6	0.4	4.4	0.2	0.3	0.05
CaO	2.4	4.4	6.9	0.3	0.4	21.5
MgO	0.2	0.3	ND	0.1	0.1	ND
Al_2O_3	10.4	17.6	13.5	13.2	12.1	24.5
SiO_2	7	14.8	3.4	4.6	4.1	14.5
Fe_2O_3	58.6	39.9	51.6	65.2	66.1	24.2
TiO_2	9.3	9.7	12.1	5.7	5.3	9
LOI@1000 °C	7.7	8.6	NA	9.4	10.3	NA
Sum	96.2	95.7	91.9	98.7	98.7	91.8
Mass reduction (wt.%)	47	54	49	24	13	59

* No direct analysis for these samples. Compositions are calculated based on liquid recoveries.

4.2 Selective Si and Al Precipitation, Circuit 1

The pregnant leach solution (PLS) from C1 treatment on S1 and S2 was selected for further processing due to its higher recovery of Al and Si. The filtrates were used to selectively precipitate Si and Al by adjusting the operational conditions. Table 4 summarizes the elemental recoveries in the mother liquid solution.

Table 4. Elemental recoveries in mother liquor after Si precipitation / Al precipitation.

	Recovery, %			
	Si - precipitation		Al - precipitation	
Sample ID	**S1**	**S2**	**S1**	**S2**
Al	81.5	78	6.1	1.6
Si	17.8	8.5	39.8	49.9
Na	95.9	89.7	98.1	99.8
Ca	96.5	77.1	99.4	99.7

Table 5 presents the chemical composition of Si-rich and Al-rich precipitates on a dry basis. XRD analysis confirmed the formation of a mixed sodium and calcium aluminum silicate phase that coprecipitates with silica gel. Recently, INNORD has developed a method to recover aluminum from the aluminum silicate phase in an extra step to avoid the loss of aluminum and to generate a higher purity silica stream. However, considering this extension remains out of the scope of this publication.

Table 5. Dry-basis chemical composition of Si-rich and Al-rich cakes (wt.%).

	Si – rich cake		Al – rich cake	
Sample ID	**S1**	**S2**	**S1**	**S2**
Na_2O	2	6.4	0.06	0.1
MgO	0.2	0.1	0.06	0.1
Al_2O_3	14.5	12.1	31.2	29.6
SiO_2	57	40.6	3.7	2.9
CaO	2.8	3.3	0.2	0.1
Fe_2O_3	0.2	0.1	0.2	0.1
LOI@1000 °C	20.7	35.2	64.1	66
Sum	97.4	97.8	99.52	98.9

The Al-rich stream underwent a caustic treatment to achieve SGA grade and regenerate reagent 1. The purification step was considered in the TEA study.

4.3 Regeneration and Recycling of Reagent 1 and Causticization, Circuit 1

The filtrate from step 4.2 was sent to a crystallizer to recover a portion of reagent 1 in the condensate and produce crystals of Na and Ca salts to be further treated with high-pressure CO_2 to regenerate reagent 1 and produce mixed Na/Ca carbonates. A solid-liquid separation system was integrated into the carbonation unit. The CO_2 consumed by the precipitation reactions is partially provided by the CO_2 produced during the rest of the process. Results showed that more than 95 % of reagent 1 was recovered during carbonation with the purity of the metal carbonate reaching 97 % after two rounds of counter-current impurity removal. Table 6 shows the composition of a carbonate stream. Water-soluble salts such as sulfates, nitrates and chlorides were the most important impurities accumulated in carbonate stream and may be removed by implementing more washing steps. The carbonate product was used for causticization to convert sodium carbonates to sodium hydroxide. Results showed that 95 % of sodium carbonate was converted to sodium hydroxide while calcium carbonates were separated using a solid-liquid

separation unit. Table 7 shows the composition of the caustic product. Higher purity caustic product could be achieved by adapting one extra washing step which has not been considered in this study.

Table 6. Chemical composition of carbonation product (wt.%).

Compound	wt.%
Na_2CO_3	77
$CaCO_3$	20
Sulfate, nitrate and chloride	3

Table 7. Chemical composition of caustic product (wt.%).

Compound	wt.%
NaOH	95.4
NaCl	3.1
Na_2CO_3	0.6
Na_2SO_4	0.4
Other Na Salts	0.5

4.4 Treatment of Fe-Rich Solid Followed by Iron Leaching, Circuit 2

The iron-rich residue from circuit 1 was dried and treated to enhance the leachability of the iron. The heat-treated solid was then leached using reagent 2 under atmospheric condition at 95 ℃ for 1 hour. Table 8 shows the recoveries of the leaching step, with iron being the primary reacted element. Rare earth elements, titanium, the remaining aluminum and silicate were further concentrated in the leach residue. The overall mass reduction after treatment in circuit 1 and circuit 2 was provided for 5 samples.

Table 8. Elemental recoveries of leaching in circuit 2, (%).

Sample	S1	S2	S4	S5	S6
Al	3.4	4.3	0.6	2.1	1.9
Ca	7.9	20.2	0	0	3.7
Fe	88.5	80.6	71.7	92.6	74.3
Na	6.9	78.2	38.2	31.8	0
Si	5.2	14.5	7.7	8	2.8
Overall mass reduction, wt.%	82	60	41	72	76

4.5 Iron Precipitation, Circuit 2

The leachate from step 4.4 was transferred to the next step to precipitate iron and regenerate reagent 2. A recovery of over 96 % was achieved for reagent 2 (Fe-leaching reagent) for most of the samples. The precipitated iron oxide was filtered and dried. Characterization of the precipitated iron powder indicated that iron oxide could exist in different phases with a wide range of particle sizes and a purity of over 99 %, making it suitable for the DRI process. Moreover, the results suggested that the properties of the iron powder could be controlled by adjusting the operational conditions of the precipitation step.

4.6 Mineral Acid |Treatment, Circuit 3

Rare earth elements, titanium and other critical metals were concentrated in the residue of step 4.5. The chemical composition of the Fe-lean sample is presented in Table 9 for sample S1. The remaining aluminum was mostly in the form of Boehmite or other spinels. The Fe-lean residue was then leached again with a mineral acid solution in both atmospheric and autoclaved

conditions to extract aluminum and REE/Sc. Table 10 shows the recoveries after atmospheric and autoclaved leaching. Sample S1 was chosen as an example for this test due to its higher contents of REEs.

Table 9. Dry-basis chemical composition of Fe-lean residue (wt.%).

Sample	S1
Na_2O	1
MgO	0.5
Al_2O_3	18.9
SiO_2	14.2
CaO	5.3
Fe_2O_3	7.2
REO	0.4
Sc_2O_3	0.3
TiO_2	21.6
LOI@1000 °C	23.9
Sum	93.3

Table 10. Elemental recoveries of a two-step mineral acid treatment, %.

	Sample S1	
Leaching step	Atmospheric	Autoclaved
Na	57.7	74.53
Ca	55.8	90.9
Al	41.2	91.7
Si	0.9	1.0
Fe	70.5	87.3
REE	56.9	99
Sc	11.7	90.8
Ti	3	11.6
V	7.8	96.3
Ga	79.8	92.1
U	51.1	69.2
Th	37	100
P	63.3	70.7

It is indicated that the majority of aluminum and REEs were leached while refractory oxides remained unleached. The results show that REEs/Sc required relatively harsh conditions to leach at higher levels of recovery. Additionally, the acid treatment was relatively selective against titanium and silica, which were components of the residue after solid-liquid separation. The filtrate, which contains Al and REE/Sc in solution, was sent to the mineral acid recycling step. After recovering over 90 % of the mineral acid, the Fe/Al mixed hydroxide was sent to circuit 1 to blend with BR feed.

4.7 REE/Sc, Gallium and Titanium Recovery

The filtrate generated in circuit 3 contains the majority of REE/Sc and gallium. REE/Sc were separated before and after the regeneration step of reagent 3 and converted into a mixed concentrate. A reliable study of REE/Sc removal and the purity of the product requires larger scale testwork since the low grade of these elements does not allow enough product to be properly characterized. Additionally, the recirculation of the reagents might introduce accumulated impurities that were not detectable on a bench scale without performing a representative reagent regeneration and recycling.

Gallium, another valuable by-product, could be recovered in circuit 3 in an additional step. However, gallium recovery remains beyond the scope of the current study, and its value was not considered in the TEA study.
Lastly, the mixture of titanium and silica could be separated to produce a smelter grade titanium concentrate, where the silica content should be reduced to less than 2 %. Research and development work are ongoing to implement the most efficient technique for this.

5. Techno Economic Analysis (TEA)

The entire BR valorization process was simulated for all 6 samples using AspenPlus V14 software to obtain detailed mass and energy balance. Experimental measurements provided most of the process parameters used to build the simulation, while thermodynamic calculations using the ELECNRTL method supplied the remaining process parameters. Error minimization algorithms were used to reconcile chemical species recoveries measured during experiments and those calculated by the simulation. Material integration was done on the process simulation to recirculate solvents and reagents, while minimal energy integration has been achieved. A factor of 0.85 was applied to the total steam and cooling water consumption to account for energy integration and optimization in future design steps. For all 6 samples, a throughput of 2 500 kt BR/year was assumed for a period of 20 years (Table 11).

Table 11. Assumptions for techno-economic assessment.

Parameter	Value
Plant capacity	2500 kt/y
Discount rate	8 %
Project duration	20 years
Cost avoided to dispose BR (USD/t)	8
Direct supervisory cost	15 % of Labor costs
Maintenance cost	3 % of CapEx
Operating supplies cost	15 % of Maintenance cost
Laboratory charges	10 % of Labor costs
Plant overhead costs	50 % of Labor, Supervisory and Maintenance costs
Administrative costs	20 % of Labor costs

A high-level capital cost estimate (-10 % / +50 %) was conducted for the entire flowsheet. Equipment costs were estimated using Aspen Process Economics Analyzer, historical costs and recent quotes from similar projects. The rest of the CAPEX was deducted from the equipment cost based on factors provided by Peters et al. [5]. This estimation excluded product shipping, transport infrastructure, permit costs, travel, legal and other corporate office charges, taxes and capital spare parts costs.

The output from the heat and mass balance model, along with the assumptions, provided the fresh reagent input and utilities requirements for the process. Energy requirements for the various grades of steam used in the process were taken from Nieuwlaar et al. [6], and the cost of steam was determined from the natural gas cost per unit of energy. Labor requirements were calculated using typical labor requirements for process equipment recommended in Peters et al. [5], while the average industrial operator salary was based on the geographical location of the refiners producing the samples [7]. Electricity and fixed capital investment cost were also adjusted to the geographical location of the aluminum refiners [8]. Chemicals purchasing prices were based on market averages [9].

The products derived from BR valorization include alumina precursor $Al(OH)_3$, NaOH 50 %, DRI-grade iron oxide, rare earth concentrate and TiO_2 concentrate. Selling prices are based on market averages, while payable percentages for each product range from 60 to 90 % depending on the product (Table 12).

Table 12. Selling price and payable percentage of the various products.

	Selling price (USD/t)	Payable %	Notes
Alumina precursor, $Al(OH)_3$	350	90 %	+99% purity
NaOH (50%)	250	90 %	
DRI-grade iron ore	150	90 %	
Rare earth elements	57 000-129 000	60 %	Basket price based on concentrate composition
TiO_2 concentrate (> 50 %)	300	90 %	

CAPEX estimations range from 1230 to 1615 MUSD (Table 13). Plant location was the most significant factor ($p = 0.003$) affecting investment costs. The amount of iron that was not leached in the iron leaching reactor also significantly impacted CAPEX ($p = 0.013$). Indeed, more unrecovered iron increases the size of the subsequent mineral acid unit, which was the section of the process with the most variability in equipment cost between the samples, as its input flowrate was directly related to the performance of previous units. Additionally, iron sent to the mineral acid unit looped back to the circuit 1 reactors, further increasing the size of the overall process.

Table13. Techno-economic analysis results summary.

Sample ID	S1	S2	S3	S4	S5	S6
Plant location factor	ND	ND	ND	ND	ND	ND
REE basket price (USD/t)	56 900	126 000	125 000	129 000	99 400	59 900
CAPEX (MUSD)	1491	1528	1615	1230	1295	1213
OPEX (MUSD/year)	279.6	282.9	288.5	415.0	290.3	351.3
Revenues (MUSD/year)	685.2	803.4	747.6	604.1	682.6	699.0
Net Present Value (NPV) on a 20-year period (MUSD)	2 688	3 836	3 244	822	2 753	2 397
Payback period, Post construction (years)	3.5	2.8	3.3	5.9	3.1	3.3

The main contributors to operating costs were utilities, which ranged from 46 % to 66 % of the total OPEX depending on the sample. Reagent costs made up 9−15 % of the total OPEX, with a major fraction (37–73 %) of these costs resulting from the loss of mineral acid. Therefore, the mineral acid recovery system, which significantly contributed to utilities and reagent costs, was a top priority for cost reduction.

Revenues from the process were distributed among the five marketable products, with no single product accounting for more than 37 % of total revenues for all samples. This distribution of revenue made the profitability results less sensitive to parameters changes. Alumina precursor was the product that generated the most revenue for all samples except S5, which had a higher iron content, thus making DRI-iron oxide its most profitable product. S2 had the highest NPV (after 20 years despite having the highest CAPEX (Table 13). This is due to the high revenues generated by a high REE basket price and a high Aluminum content in the feed. On the other hand, S4 had the lowest NPV after 20 years, with also the lowest revenues and the highest OPEX (Table 13). The low iron recovery in the iron leaching reactor, along with a low REE concentration in the feed explained the high costs and relatively low revenues. Therefore, it appears that feedstock composition and Al/Fe recoveries in circuit 1 and 2 are the parameters that have the greatest impact on the overall profitability of the BR valorization process.

Table 14. TEA results per process circuit.

Process Step	Indicator	S1	S2	S3	S4	S5	S6
C1	CapEx (MUSD)	735.1	679.6	699.8	366.5	422.1	569.5
	Volume reduction (%)	45 %	56 %	66 %	16 %	10 %	71 %
	NPV (MUSD)	366.4	1143	692.1	288.5	-300.6	-545.0
	IRR	14 %	27 %	20 %	17 %	-5 %	-17 %
C1+C2	CapEx (M$)	945.6	804.9	956.2	526.2	707.2	664.5
	Volume reduction (%)	78 %	71 %	83 %	63 %	73 %	79 %
	NPV (MUSD)	689.5	1201	727.6	745.2	700.7	-504.6
	IRR	17 %	25 %	17 %	24 %	20 %	-6 %
C1+C2+C3	CapEx (MUSD)	1491	1528	1615	1230	1295	1213
	Volume reduction (%)	96 %	93 %	96 %	98 %	99 %	92 %
	NPV (MUSD)	2687	3779	3089	822.3	2753	2397
	IRR	28 %	35 %	29 %	16 %	32 %	30 %

Separating the economic indicators per circuit highlighted the need to develop the process in its entirety and maximize the value of all possible products (Table 14). For all samples, profitability indicators showed a significant improvement as more circuits were added to the process. A large portion of the aluminum valorized in the process was extracted during the mineral acid leaching in C3 circuit. C3 circuit also generated REO and TiO_2 concentrates which contributed 25–44 % of the revenues, depending on the sample. C1 circuit, which included generally the most capital-intensive of the three circuits, accounting for 34–52 % of the total CapEx. High volume reduction in C1 was generally associated with better economics except for S5, which had a high iron content. This made the iron extraction circuit (C2) the most revenue-generating section of the process. For S6, having all three circuits was crucial for positive economic indicators. This was because of its low Aluminum recovery in C1, making the $Al(OH)_3$ production triple after mineral acid leaching in C3. REO and TiO_2 concentrates also accounted for 44 % of the total revenues and thus highlighted the need to have all three circuits of the process. Hence, high product recovery in the process coupled with a good material integration between the process circuits are important parameters that had a profitable process.

6. Life Cycle Impact Analysis (LCIA)

A life cycle analysis was conducted on all six samples to evaluate the overall impact of the BR treatment process on the environment in accordance with ISO 14040-44. The analysis scope was gate-to-gate, with the first gate at the BR inlet and the final gate at the point where the products exit the process to be sold. Background inventory data was sourced from the Ecoinvent 3.11 database [10], and foreground data was obtained from mass balance generated by Aspen Plus simulation. The impact assessment method utilized was TRACI 2.1 [11], which converts emissions into midpoint indicators. The functional unit was defined as ‘the treatment of 1 tonne of dry BR’ (Table 15), and the impact evaluation method was consequential rather than attributional. Reagent transportation distance was assumed to be 250 km.

Table 15. Functional unit and products of the BR treatment plant.

Sample ID	S1	S2	S3	S4	S5	S6
Avoided BR disposal (t/t BR)	1	1	1	1	1	1
$Al(OH)_3$ (t/t BR)	0.249	0.375	0.323	0.257	0.248	0.329
NaOH (50 %) (t/t BR)	0.214	0.164	0.152	0.119	0.047	0.171
DRI-iron oxide (t/t BR)	0.398	0.171	0.278	0.543	0.617	0.104
TREO (kg/t BR)	1.6	0.94	0.92	0.29	0.96	1.5
TiO_2 concentrate (t/t BR)	0.15	0.266	0.208	0.141	0.105	0.252

Table 16 displays the gate-to-gate direct environmental impacts per ton of BR for all six samples. System expansion was accounted for the environmental impact assessment. As depicted in Figure 2, utilities were the primary contributors to GHG emissions and several other impact categories. Leaching reagents also played a significant role in environmental impacts, emphasizing the importance of optimal reagent regeneration. Although impact distribution was only presented for S1, similar conclusions could be drawn for the other samples.

Table 16. Direct environmental impacts per ton of BR, without system expansion.

Sample ID	S1	S2	S3	S4	S5	S6
Acidification (kg SO_2 eq/t BR)	1.6	2.03	2.07	2.33	1.85	2.51
Climate change (kg CO_2 eq/t BR)	1500	1680	1660	2210	1680	1590
Ecotoxicity: freshwater (CTUe/t BR)	4410	7210	7780	7610	6170	7270
Eutrophication (kg N eq/t BR)	1.13	1.56	1.76	1.93	1.96	1.77
Carcinogenics (CTUh/t BR), ($\times 10^4$)	1.20	1.53	1.60	1.80	1.40	1.50
Non-carcinogenics (CTUh/t BR), ($\times 10^4$)	0.684	1.19	1.30	1.30	1.10	1.30
Ozone depletion (kg CFC-11 eq/t BR), ($\times 10^4$)	0.188	0.467	0.464	0.488	0.353	0.41
Particulate matter formation (kg PM2.5 eq/t BR)	0.169	0.312	0.332	0.538	0.262	0.341
Photochemical oxidant formation (kg O_3 eq/t BR)	42.2	49.1	49.6	55.7	45.6	55.5

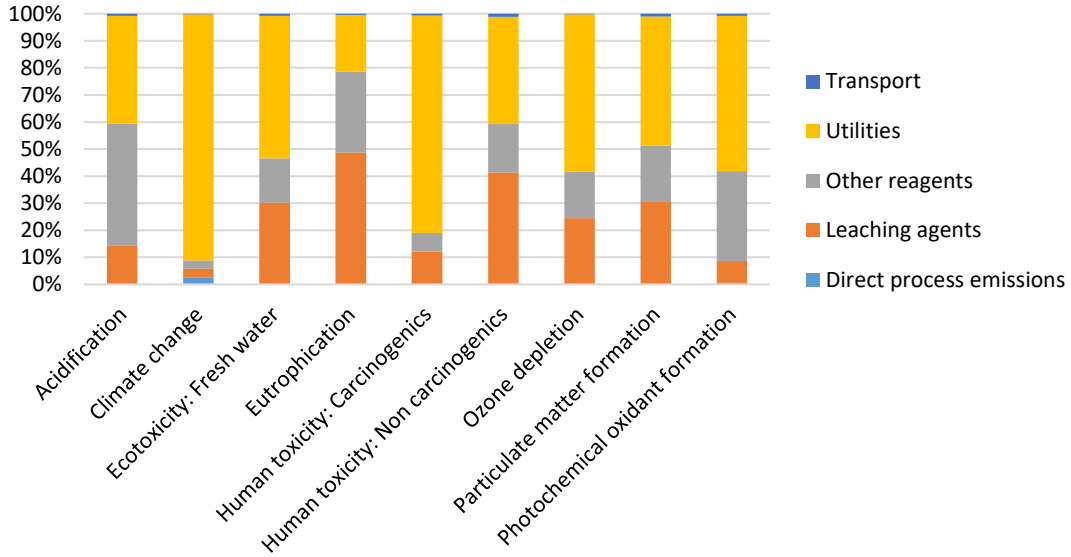

Figure 2. Impact repartition for sample S1, BR valorization process, without system expansion.

System expansion was utilized to address allocation issues to evaluate the overall impact of the process on the environment. This approach assumes that products derived from the BR valorization process will eliminate the need for BR disposal operations and replace current fresh products. Since most products from the BR valorization process were bulk products with established global markets, introducing these new products into the global value chain should not disrupt supply chains. This justified the use of system expansion.

The $Al(OH)_3$ product replaces $Al(OH)_3$ produced from the conventional Bayer process, and NaOH replaces the traditional NaOH product. The iron product replaces iron pellets, while TiO_2 concentrates are considered as substitutes for ilmenite containing 54 % TiO_2. The environmental impacts arising of REE concentrates were compared to the average environmental impacts associated with the production of 50 % rare earth oxide concentrates. Avoided BR disposal operations were also taken into account in the system expansion (Table 17).

Table 17. System expansion processes impacts.

	Disposal	Production				
Sample name	**BR**	**$Al(OH)_3$**	**NaOH (50 % wt.)**	**Iron pellet**	**Rare earth concentrate**	**Ilmenite 54 % TiO_2**
Acidification (kg SO_2 eq/t)	0.04	4.79	6.72	0.968	38.8	1.16
Climate change (kg CO_2 eq/t)	6.87	605	1390	95.6	3740	139
Ecotoxicity: freshwater (CTUe/t)	137000	114000	30900	1580	83100	1670
Eutrophication (kg N eq/t)	4.23	4.92	6.85	0.594	15.0	0.339
Carcinogenics (CTUh/t), ($\times 10^4$)	76.8	62.5	4.28	0.194	5.70	0.441
Non-carcinogenics (CTUh/t), ($\times 10^4$)	9.13	9.11	6.28	0.346	28.4	0.299
Ozone depletion (kg CFC-11 eq/t), ($\times 10^4$)	0.0017	0.111	1.50	0.017	0.508	0.0381
Particulate matter formation (kg PM2.5 eq/t)	0.0069	0.576	1.87	0.948	15.6	0.14
Photochemical oxidant formation (kg O_3 eq/t)	1.24	55.5	94.8	17.8	1107	25.8

Table 18 displays the total environmental impact of the BR valorization process after system expansion for all six samples. Generally, the process increased global GHG emissions by 1 to 1.83 t CO_2 eq/t BR, mostly due to steam generation from natural gas combustion. The climate change indicator score was highly correlated with OPEX (correlation factor = 0.906), as they were both highly dependent on utilities consumption. This made S4 the most carbon-intensive process, and S1 the least, following the same trend as OPEX. A net decrease was observed for almost all impact categories other than climate change. This is due to the low amount of fresh reagent input and the high BR mass reduction avoiding the emission of various impactful chemicals into the different environmental containers. Impact score normalization was applied to the LCIA results to assess the net general environmental balance of the process [12]. Although impact normalization must be carefully interpreted, a general negative trend in environmental impacts was noted for all samples when considering the total normalized impact score. This suggested that, even though there was an increase in GHG emissions compared to the use of typical products, there was a net environmental advantage in valorizing BR, regardless of the sample. Finding ways to reduce fossil fuel consumption for utilities and process heat integration to decrease net utility load were the prime ways to further improve the LCIA results towards a more sustainable process.

Table 18. Environmental impacts per tonne of BR, after system expansion.

Sample name	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Acidification (kg SO_2 eq/t)	-1.52	-1.43	-0.847	-0.284	-0.335	-0.423
Climate change (kg CO_2 eq/t)	1001	1159	1221	1831	1391	1134
Ecotoxicity: freshwater (CTUe/t)	-168 100	-178 200	-171 000	-163 000	-161 400	-172 600
Eutrophication (kg N eq/t)	-6.05	-5.84	-5.27	-4.71	-4.19	-5.34
Carcinogenics (CTUh/t), ($\times 10^4$)	-92.1	-99.5	-96.0	-91.7	-91.2	-96.6
Non-carcinogenics (CTUh/t), ($\times 10^4$)	-12.2	-12.6	-11.9	-11.1	-10.8	-12.0
Ozone depletion (kg CFC-11 eq/t), ($\times 10^4$)	-0.169	0.164	0.194	0.270	0.243	0.113
Particulate matter formation (kg PM2.5 eq/t)	-0.782	-0.432	-0.421	-0.359	-0.576	-0.298
Photochemical oxidant formation (kg O_3 eq /t)	-1.98	-0.486	10.1	18.9	14.0	16.1
Total normalized impact score ($\times 10^4$)	-0.128	-0.137	-0.132	-0.125	-0.125	-0.133

7. Conclusion

The proposed bauxite residue valorization process was proven to be technically feasible, economically profitable and environmentally viable for a variety of BR samples, including fresh samples and those from legacy sites. The recovery of aluminum hydroxide, NaOH (50 %), DRI-grade iron oxide, REO and TiO_2 concentrates reduced waste volume by more than 85 %, offering a solution to the accumulation of disposed BR. The high level of integration between the various process units maximized the extraction of products while reducing the need for fresh reagents. Experimental testwork on six BR samples validated the performance and versatility of the valorization process, providing data for simulation of all major process steps.

The economic assessment of the process enabled by simulation, demonstrated that the process is generally profitable on a larger scale, with poste-construction payback periods ranging from 2.8 to 5.9 years. The yield of the iron leaching reaction was shown to be one of the process parameters with the most significant impact on profitability, along with plant location and BR composition. Consequential life cycle analysis showed that BR valorization results in a net decrease in environmental impacts, despite the high utility demand of the process, leading to increased total GHG emissions. As process heat was assumed to be generated by fossil natural gas combustion, transitioning to less carbon-intensive utilities would directly reduce the environmental impacts of the plant. Further optimization of the process parameters identified in the TEA would decrease technical and economic risks, with process scale-up as the ultimate objective.

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