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Ex-Situ CO_2 Capture and Utilization Over the Bauxite Residue: Lifecycle and Economic Recovery Assessment

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ABSTRACT

Carbon-dioxide Capture and Utilization (CCU) technology is an efficient process in the portfolio of greenhouse gas reduction approaches and is programmed to mitigate global warming. Given that the prime intention of CCU technologies is to prevent CO_2 emissions into the atmosphere, it remains to be seen if these approaches cause other environmental impacts and consequences. Therefore, the Life Cycle Assessment (LCA) approach was considered to account for all environmental aspects, in addition to the emission of greenhouse gases. In this study, the Life Cycle Inventory (LCI) methodology was employed to quantify the environmental impacts of indirect carbonation of Red Mud (RM), a waste byproduct of alumina production line in Jajarm Alumina Plant, Iran by CO_2 exhausted from the plant stacks based on International Organization for Standardizations (ISO) of ISO 14040 and ISO 14044. The results confirmed the reduction of CO_2 emission by 82 %. The study of carbon footprint based on ISO 14064 under the criterion of PAS 2050 revealed CO_2 emission equivalent to 2.33 kg/ ton RM, proving that CCU managed to mitigate the CO_2 emission by 93 % compared to the conventional technology employed in Jajarm Plant, which produced around 34 kg CO_2 per 1 ton RM. Furthermore, the economic evaluation of the process brought about 243 $/ton RM in profit via the sales of products including silica, aluminum, hematite, and calcium carbonate. The outcomes of the present study highlight that the intended CCU technology is a practicable approach for large-scale applications.

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1. INTRODUCTION

Anthropogenic activities increase the emission of greenhouse gases (GHGs) into the atmosphere, which is one of the major causes of global warming. This is a crucial problem for the future of the earth and living species. Carbon dioxide, methane, nitrogen oxide, and halocarbons are the main GHGs, among which CO_2 is the most problematic GHG in terms of global warming. According to a report by the Intergovernmental Panel on Climate Change, the concentration of CO_2 in the atmosphere will reach 2100 ppm by 2100 [1]. In order to keep the average increase rate in the global temperature below 2 °C, the emission of CO_2 should be reduced by 50-85 % before 2050. In this respect, different strategies have been taken into practice to ensure the sustainability of the world climate [2–4]. These recommended strategies include reduction of requisition process, efficiency improvements, application of renewable sources, nuclear power, and Carbon Capture and Storage (CCS). CO_2 capture at the terminal point of industrial processes such as power plants, cement manufacturers, refineries, and steel mills in which an immense volume of CO_2 is exhausted could be one of the potential solutions for the management of global warming [5–7].

The CCS and CCU technologies are noteworthy and promising approaches to reducing GHG emissions. These techniques have received a warm welcome by many industrial communities [8]. Although CCS is an efficient technique for the reduction of CO_2, it is not a satisfactorily viable method in terms of some technical and economic barriers for large-scale applications. From an economic standpoint, it is a high-cost process with no profit that cannot attract industries to invest. From a technical viewpoint, the leakage of CO_2 and obstacles regarding the storage of captured CO_2 are the common limitations of this process. A promising alternative that has attracted many industries is CCU processes. This is because CCU technologies act successfully in CO_2 reduction and are economically rewarding methods as the production of value-added products during the process and trading them to the marketplaces return a part of the investments. These commercial products have made CCU technologies more affordable than the CCS approaches. In addition to this merit, CO_2 released from different flues can be used as a renewable energy source, which is an inexpensive and non-poisonous available source. Moreover, the precious merits of this approach such as the availability of CO_2 as a safe resource that can compete with low-price fossil fuels motivate researchers to direct their researches to CCU techniques [9–12].

An effective method that has been widely expanded for CCU goals is mineral carbonation practices. Mineral carbonation is a natural weathering process in which the reaction of CO_2 with natural alkali rocks leads to the formation of carbonate rocks for a relatively long time [13]. Natural alkali sources are known as rocks with a high amount of magnesium and calcium in the form of silicate minerals such

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as serpentine, olivine, and wollastonite. This natural phenomenon has inspired researchers to establish a mineral carbonation process for the capture and storage of industrially emitted CO_2 over alkali minerals [14]. Two typical mineral carbonation methods are direct and indirect carbonation. The direct mineral carbonation consists of carbonation reactions taking place in a single step, while, indirect mineral carbonation proceeds in a multi-stage process. To be more specific, in the direct carbonation process, the extraction of metals and carbonation reactions proceeds in one reactor vessel at the high pressure. In contrast, indirect carbonation embraces reactions in several discrete steps. The first step is the leaching of minerals from the alkali waste by a suitable acid. Common acids include hydrochloric acid, sulfuric acid, nitric acid, acetic acid, ammonium chloride, oxalic acid, citric acid, ammonium acetate, sodium citrate, sodium acetate, ammonium citrate, and ammonium oxalate [15]. The second step, called the pH swing process, concerns the formation of metal hydroxides by the addition of basic agents to reach high-purity alkali metal (calcium or magnesium) solution. The third and final stage includes the carbonation reaction in which CO_2 reacts with alkali metals resulting in the creation of carbonates (namely calcium/magnesium carbonate). The characteristic benefit of this approach is the storage of CO_2 in the form of highly stable carbonates for quite a long time with no probability of CO_2 release and leakage to the atmosphere. The other privilege of the indirect mineral carbonation is that there is no need to separate CO_2 from the flue gas for obtaining high-purity CO_2 because impurities present in CO_2-containing effluent gas such as SO_x and NO_x cannot interfere with the carbonation process. Hence, the exhausted gas can be directly used without any extra purification process which will save cost and energy. In spite of the limitations owing to the high cost and energy penalty of this process for industrial application, the mentioned merits have attracted scientists' attention to put their effort into upgrading the process or a large-scale utilization [16–19].

It has been reported that an industry armed with CCS technique changes the emission pattern of CO_2 [3]. In the industrial application of a CCS or CCU, in addition to climate change, other environmental impacts should be considered to see whether the relief of climate change induces other environmental consequences or not. A powerful tool to facilitate proper recognition of the environmental impacts of CCS/CCU is the deployment of the LCA approach [20,21]. In the LCA approach, the environmental impacts of a product system or device during its life cycle from the cradle to the grave including extraction of raw materials, transportation, production, distribution, and disposal of wastes are considered [22–24]. Emissions and resource usage in all of these stages and their proportions relevant to the specific environmental impacts should be included in the life cycle inventory (LCI) [25,26]. LCA is a precious tool for decision-makers as it assists them to choose among the proposed options [27,28], and for the simple judgment and comparison of the processes, several standards were introduced such as International Organization for Standardizations (ISO) [25,26]. LCI characterizes environmental inventories which are itemized as follows: abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FWAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TEP), photochemical oxidation potential (POP), acidification potential (AP), and eutrophication potential (EP) [3]. In addition, economic evaluation has been considered as a key strategy for the estimation of the process potential for real application and its economic recovery [29–31].

In the current study carried out for the first time, 1) environmental impacts of indirect carbon mineralization of RM, the waste of Jajarm plant, were assessed by the LCA methodology. 2) The carbon footprint quantification was employed for a better understanding of GWP by calculation of GHG emissions of CCU under the boundary of the system. 3) The economic investigation was carried out to estimate the pecuniary value of the products and the cost compensation of the initial investment. 4) The outcomes of this study are highly beneficial to predicting the feasibility of the CCU process for commercial and real applications in the Jajarm plant.

2. ALUMINA PRODUCTION PLANT

Bayer method is the most common method in the production of aluminum from the bauxite mineral source. Bauxite is a well-known aluminum ore containing 30 to 54 % alumina and different percentages of silica, iron oxides, and titanium dioxide. In this method, sodium hydroxide solution at a temperature of 175 ºC is used to wash the bauxite rock and convert alumina into aluminum hydroxide, which is soluble in sodium hydroxide solution. Other components of bauxite ore are not soluble in sodium hydroxide solution; therefore, they can be separated from aluminum hydroxide by filtration. The aluminum hydroxide powder is obtained via cooling and, then, is heated to 980 ºC to separate alumina and water in order to achieve pure alumina.

$$2\,Al(OH)_3 \rightarrow Al_2\,O_3 + 3\,H_2O \quad (1)$$

Alumina plant of Iran (Jajarm complex) is the only alumina production plant in Iran, which is located in Jajarm, North Khorasan. It was established in 2003 with the alumina production capacity of 280,000 ton/ year. The Jajarm plant produces alumina via the Bayer method and it needs 348,000 ton of ground lime per 1 ton of alumina. About 500,000 ton of RM is produced annually and about 7 million ton of RM has been accumulated so far [32]. The composition of RM produced by the Jajarm plant was tested by XRF analysis (Table 1) and results confirm the great potential of RM for CCU as it is rich in calcium. The Jajarm plant includes seven main operational units, which are bauxite, dissolution, separation of RM, sedimentation, calcination, evaporation, desalting, and utility. Figure 1 depicts the overall process of alumina production of the Jajarm plant.

Table 1. XRF analysis of RM.

Component	Composition (wt %)
Fe_2O_3	35.77
CaO	14.21
Al_2O_3	15.88
L.O.I	10.61
SiO_2	11.73
Na_2O	5.28
TiO_2	4.41
MgO	1.24
Cl	0.17

3. LIFE CYCLE ASSESSMENT

3.1. Methodology

LCA has been introduced as a holistic evaluating method which appraises all resources, emissions, and energy streams and their environmental consequences throughout the life cycle of a certain product or service or system [33]. LCA calculates resource usage and environmental emissions in all steps ranging from raw material consumption to waste disposal during the entire life cycle of a product. Figure 2 shows the life cycle stages of a product briefly. This is a remarkable decision-making tool that allows institutions and program developers to take a vivid perspective regarding the environmental damage of a product [26,34,35].

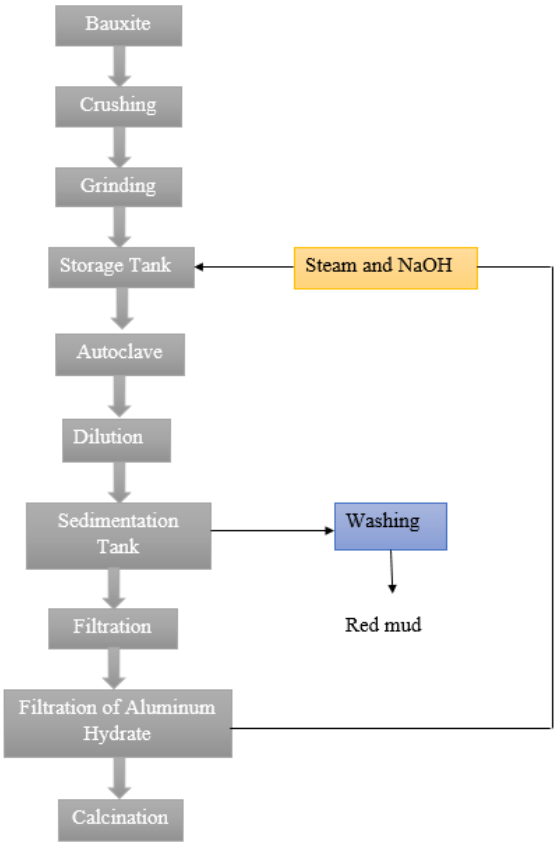

Figure 1. The overall process of alumina production of the Jajarm plant.

Figure 2. The stages of the life cycle of a product.

Owing to the widespread applications of the LCA method, several ISO standards have been described to help researchers to apply proper LCA criteria. Due to the complexity of the quantification process, accession of computer-aided technologies is truly beneficial due to their high accuracy and simplicity. The computational software weights the target process for its sustainability, LCA, and environmental impacts. Among the computational tool, GaBi tenders a simple, precise, and fast analysis for LCA and inventory assessment of a product system [36]. In this study, LCA was carried out based on the standards of ISO 1404 and ISO 14044 and the scenario is outlined as in the following steps:

1. Specification of the goal and scope: The initial attempt in LCA is the accurate specification of the aim of the LCA implementation for a given product and ascertaining of the system boundaries.
2. Life cycle inventory (LCI): In this step, all environmental inventories and inputs and outputs of the given product system are quantified. This stage is highly complicated since many elements in each life cycle stage should be accounted which necessitates a comprehensive database set to model the value chain of the processes. However, all the essential databases are not available. In such cases, LCA proceeds by postulating the ungiven data and checking the accuracy of the assumed data via the sensitivity analysis.
3. Life cycle impact assessment: The next step is the measurement of the environmental impacts resulting from interventions. This assessment embraces the classification of analogous interventions of a system in a category including global warming, acidification, etc. and calculation of those environmental impacts. The environmental impacts are classified as the items described in Table 2. A concise explanation of some of these categories is described below [20,26,37].

Global warming

The unpleasant phenomenon of global warming is entangled with the emission of greenhouse gases. The global warming categorization in LCA is estimated as the equivalent CO_2 through the assessment of the global warming potential of each chain during 100 years. Indeed, the environmental impact of global warming defined by the LCA just focuses on the emission of greenhouse gases resulting from human activities. Different greenhouse gases possess different potentialities in global warming. Therefore, the calculation of their contribution is comparatively complicated. The main greenhouse gases include CO_2, CH_4, and N_2O and the global warming potential attributed to them are defined as 1, 25, and 298 kg of equivalent CO_2 per kg of substance [38].

Resource depletion

In order to specify the resource depletion, the collection of the value of all energy inputs such as fossil fuels involved in the manufacture of the system is calculated.

Smog air

Smog air is a phenomenon associated with the formation of near-ground ozone (photosmog or summer smog). The ozone equivalent is the parameter used for the quantitative study of the environmental impact of the ozone creation potential of the system.

Acidification

The release of acidic substances, known as proton, into the atmosphere is called acidification. This impact is addressed in LCA as kg of equivalent SO_2. The acidic materials such as SO_2, NO_x, HCl, H_2S, and NH_3 are considered in this category with acidification potentials of 1, 0.7, 0.88, 1.88, and 1.88 kg of equivalent SO_2 per kg of substance, respectively [38].

Eutrophication

The increase of the phosphoric and nitric contents of water and soil is known as eutrophication. This increment disarranges the natural balance of the ecosystem's components, which can give rise to the challenging issues. In

the LCA studies, eutrophication of water and soil is defined as two separate parameters. In this study, air-oriented emissions were taken into account as the main cause of the soil eutrophication. The equivalent kg of $PO4^{3-}$ was used to address soil eutrophication.

Human toxicity

Human toxicity in LCA methodology is described as the toxic impacts of components on human health in a way that shorts human lifetime. This term is divided into two categories of cancer and non-cancer diseases.

4. Interpretation of the results: The final stage is the interpretation of the obtained values and quantities in order to make a comprehensive deduction and figure out the deficiencies. A beneficial strategy in order to judge the deficiencies is known as the sensitivity analysis [38].

Table 2. The life cycle impact categorizations.

Life cycle impact category	Unit
Global warming	Tons of CO_2 equivalents
Stratospheric ozone depletion	Tons of Halon equivalents
Ground level ozone	Tons of projected ozone
Acidification	Tons of SO_2 equivalents
Eutrophication	Tons of phosphate equivalents
Aquatic toxicity	Tons of toxic equivalents
Human health	Equivalent tons of toxics
Fossil fuel depletion	Tons of oil equivalent
Mineral depletion	Tons of mineral equivalent (by mineral)
Water depletion	Cubic meters of water equivalent, (surface & groundwater)
Land use	equivalent hectares of endangered species and non-endangered species habitat
Resource depletion	Equivalent energy

3.2. Goal and scope of LCA

The aim of this LCA study is the projection of the environmental footprint of the carbonization of RM via an indirect route which could be beneficial in the future perspective of Jajarm Alumina Production Plant equipped with CCU technology. In this study, the specific environmental impacts of carbon capture via LCA were investigated and categorized based on different environmental classifications by GaBi software based on the ReCiPe methodology.

3.3. Process description and boundary

A proper process boundary designation is the key step in the cogent conclusion of an LCA study [39,40]. Figure 3 describes the system boundaries of the CCU process of the Jajarm plant. This process boundary covers the transfer of RM residue over the distance of about 1 km to the place that flue gas of the plant is exhausted and final calcium carbonate and side-products are produced. A brief description of the process is given below:

1. The RM extraction for leaching precious minerals including Al, Fe, and Ca was carried out using HCl (1M) at 80 °C at the initial step of the mineral carbonation. Indeed, 21 g dry powdered RM was added to the reactor comprising HCl and was agitated at a speed of 600 rpm by a magnetic stirrer upon atmospheric pressure. The reactor was covered with a condenser to prevent evaporation occurrence and preserve the temperature at a constant level as this reaction is exothermic. After completing the extraction in 2 h, the resultant slurry was separated from solid particles via centrifuging (9900 rpm, 15 min) and, then, vacuum filtration.
2. The second step concerns the production of Ca-enriched solution via the pH swing process. To be more specific, NaOH (1M) was employed to precipitate impurities present in the leached solution. pH increased from 2.3 (initial pH of the solution) to 4, 5, 7.5, and 9.5. At each step, the precipitants were separated using centrifuging (9900 rpm, 15 min) and vacuum filtration.
3. Next, the CO_2 recovery from the stacks (stacks A, B, and C) of the Jajarm plant was taken into account. The recovery of CO_2 from the stacks of the plant was performed via an amine scrubbing column. A mixture of CO_2 (10 % Vol.) and N_2 with a flow rate of 2 l/min was fed into the bubble column filled with 20 L of NaOH (1M). The conversion rate of CO_2 was about 99.53 %.
4. The suggested process ended in the production of the stabilized calcium carbonate. The reaction proceeded in ambient conditions to avoid any extra regulation with respect to the reaction conditions and, accordingly, less energy was required for the process. The prepared Na_2CO_3 was added to the final ca-enriched leachate, obtained in the first step, at a rate of 20 ml/min over a magnetic stirrer (250 rpm). After the reaction, a milky solution and white solid of Ca_2CO_3 were obtained which were centrifuged and filtered using a vacuum pump [13]. The conversion rate was achieved at 32.71 %.

The resultant product was transported to trucks to carry it for further commercial applications. It is noteworthy to mention that the environmental impacts relevant to those applications which utilized calcium carbonate product were not included in LCA. The functional unit was selected based on 1 t RM.

4. CARBON FOOTPRINT

The carbon footprint calculates GHG emissions during the life cycle of a product system or device [6,41]. This is a simple approach that includes carbon emissions as well as other non-carbon GHG emissions; however, the results are reported as the CO_2 equivalent [42,43].

According to the GHG Protocol Product Standard, there are obligations with respect to the emission of GHG. The carbon footprint strategy has been developed as the momentous agenda of societies in order to reduce the rising amount of CO_2 in the course of the life cycle of a product, system, or service [44].

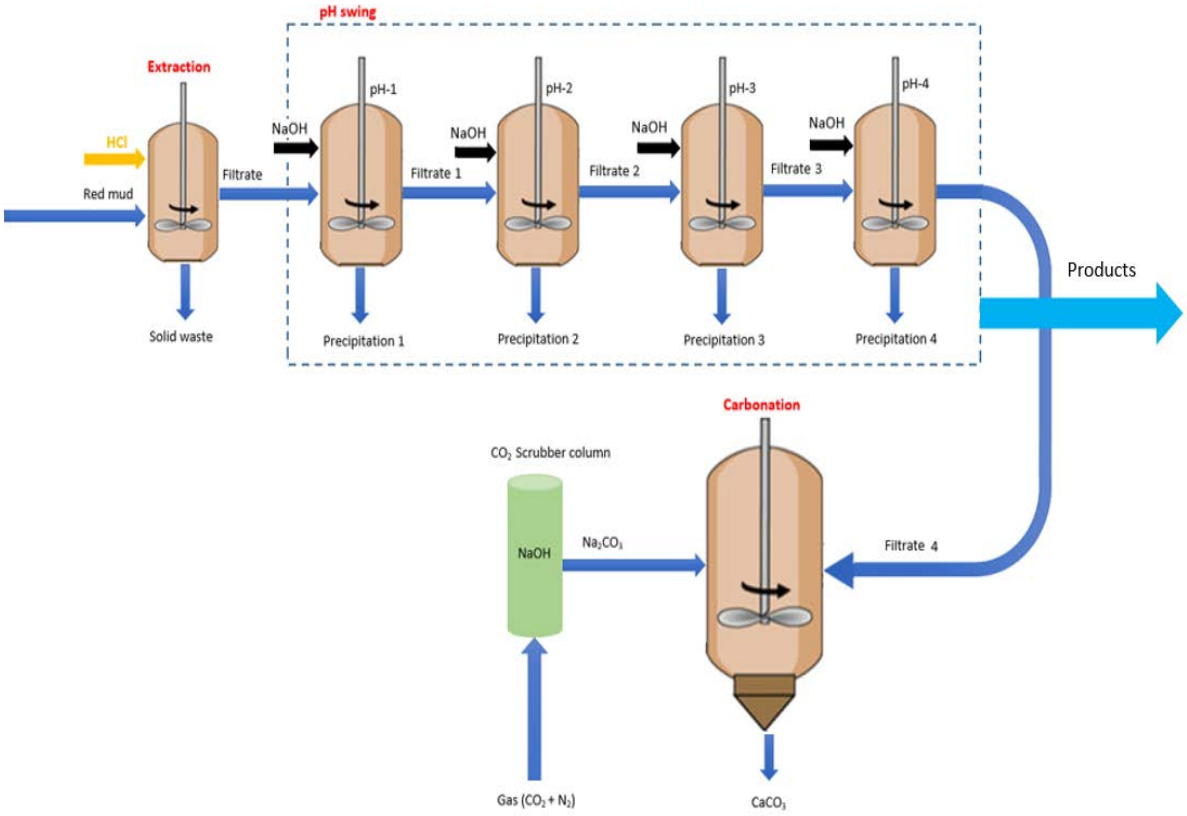

Figure 3. Schematic diagram of the system boundary of LCA.

4.1. Methodology

The applied methodology for carbon footprint assessment in the current study is the Publicly Available Specifications (PAS) 2050. The LCA methodology cataloged in ISO 14040 based on the PAS 2050 framework is a highly attended standard for assessing products' carbon footprint. Although the ISO 14040 series represent the significantly applied LCA guidelines for the estimation of GHG emissions of a product or service, they lack a proper and accurate basis for the assessment of GHG emissions for the developing projects. An alternative standard exerted for assessing GHG emissions is ISO 14064 which considers carbon footprint at the organizational level. ISO 14064 seeks to provide institutions with a comprehensive assessment of direct and indirect GHG emissions of a product or service during the LCA and suggest strategies for mitigating GHG emissions. In the current study, ISO 14064 under the PAS 2050 criteria was used for the assessment of GHG emissions of RM carbonation process, which is expressed in CO_2 equivalent according to the GWP of each GHG defined by IPCC [41]. The tiers of GHG emissions based on ISO 14064 are illustrated as the following items: Tier 1) direct emissions from resources presented inside the system boundary; Tier 2) indirect emissions related to the energy use of an operational sector such as consumption of electricity, heat, and steam required for the production of a product; Tier 3) indirect emissions attributed to sources or operation of sectors beyond the allocated system boundary.

The emission equation according to ISO 14064 is defined as follows:

$$E_{tot} = \sum(EF_i \times AF_i) \quad (2)$$

where E_{tot} is the total emission of the process, and EF_i and AF_i are the emission factor and the activity factor of the individual resource of i, respectively [45,46].

4.2. System boundary and functional unit

ISO 14064 delineates the carbon footprint system boundaries as two specific boundaries, namely the organizational boundaries and the operational boundaries. The organizational boundaries are assigned to identify facilities of an organization that cause GHG inventory and they should be considered in the inventory analyses. According to the equity share definition, ISO 14064 takes the systems or devices under consideration which possesses the GHG emissions' portion of above 1 % of the predicted emissions of the functional unit.

The operational boundaries specify activities involved in the GHG inventory. In this context, direct emissions of GHG and those indirect emissions due to the supply of essential energies such as heat, steam, or electricity for the production of a product are considered in inventory calculations. The indirect emissions of GHG associated with the activities outside the defined boundary may or may not be taken into account. It is worth noting that the indirect emissions resulting from electricity generation should be cited, but the citation of other emissions is optional, e.g., consideration of capital goods, transportation vehicles of employees or costumers [47,48].

The allocated system boundary for the carbon footprint of carbon mineralization of the Jajram plant was the same boundary defined in the LCA study (see Figure 1). As described before, PAS 2050 criteria just quantify the emissions of systems or devices that cause the GHG emissions beyond 1 % of the anticipated emissions for the functional unit. Additionally, the emissions associated with capital goods such as the construction of site and infrastructure and transportations were not taken into account. In the current study, no direct emission was accounted for in the process since none of the facilities consumed energy directly. Therefore, no direct emissions were expected. The only source of GHG emissions in this process was related to electricity use. As discussed above, the required energy for electricity generation out of the boundary of the system is considered as indirect GHG emissions. In order to compute the amount of indirect GHG emissions related to electricity consumption, the electricity use of all electrical facilities and the emission factor of each facility were used [49]. The emission factor can be calculated according to the following equation:

$$E_{ID,GE,CO_2} = \frac{EI_{grid} \times EF_{GE,CO_2}}{1-TDL} \quad (3)$$

where E_{ID,GE,CO_2} is the indirect emission of CO_2 resulting from the utilization of electricity, E_{ID,GE,CO_2} is the emission factor of the electricity network (ton $_{CO2}$/ MWh), EI_{grid} is the amount of received electricity (MWh), and TDL is the electricity loss.

According to the balance sheet of China in 2016, E_{ID,GE,CO_2} and TDL were considered as 0.6607 and 0.123, respectively.

5. RESULTS AND DISCUSSION

5.1. LCA methodology

The results of the simulation of the ex-situ CCU process of the Jajarm plant are given in Table 3. Table 3 summarizes the details of each environmental impact category assessed by GaBi software. As was mentioned in our previous work [13], the CO_2 mineralization process was intended to capture CO_2 to prevent the increase of global warming. Accordingly, the climate change category was chosen as the most critical life cycle impact for comparison and decision. According to the LCI results, compared to the conventional process that produced 34 kg CO_2, with equipment of the process with CCU, CO_2 eq. emission reduced about 28.13 kg/ ton RM, which means around release of 82 % CO_2 eq. into the atmosphere can be avoided. Moreover, the results showed that the share of each step in emission was about 40.2 %, 29.3 %, 24.6 %, and 5.9 % for pH swing, scrubbing column, extraction, and carbonation steps, respectively.

Table 3. The results of life cycle impact categories for the proposed CCU process.

Life cycle impact category	Value	Unit
Climate change (ind. biogenic carbon)	5.87×10^{0}	kg CO_2 eq.
Acidification	1.54×10^{-3}	Kg SO_2 eq.
Ozone depletion	6.3×10^{-9}	kg CFC-11 eq.
Human toxicity, cancer effects	2.52×10^{-11}	CTUh
Human toxicity, non-cancer effects	1.3×10^{-10}	CTUh
Human health, Particulate air	1.14×10^{-5}	kg PM2.5 eq.
Eutrophication	2.24×10^{-3}	Kg N eq.
Smog air	2.52×10^{-3}	kg O_3 eq.
Ecotoxicity (freshwater)	1.31	CTUe
Resource depletion, mineral, fossil, and renewable	3.67×10^{-7}	kg MJ surplus energy eq.

5.2. Carbon footprint methodology

The CCU technology reduces the CO_2 emission of the Jajarm Plant. The CHG emissions during the CCU process were calculated based on the PAS 2050 scenario using ISO 14064. The total equivalent emissions associated with the main electricity-consuming instruments are summarized in Table 4. The total equivalent CO_2 emission is 2.33 kg which means a reduction of about 93 % of the equivalent CO_2 emission to the atmosphere. This value is lower than the results acquired by LCA in the climate change category. This is due to the fact that carbon footprint considers the emissions related to electronic consumption, while LCA is a holistic analysis. Therefore, the total emission estimated by LCA is higher than the carbon footprint.

Table 4. The results of carbon footprint methodology for the essential apparatus.

Instrument	Equivalent emission CO_2 (ton CO_2eq/1 ton extraction)	EI_{grid}	Consumed electricity (MW)	Consumed time (min)
Electrical stirrer	0.0011	0.0015	0.003	30
Industrial centrifuge	0.0011	0.0015	0.006	15
Scrubber column	0.00013	0.0011	0.00035	30

5.3. Economical assessments

The process of CCU of CO_2 emitted from the stacks of the plant was considered in an indirect mineralization procedure. One of the best privileges of this process is its low capture cost as it proceeds in ambient conditions, namely environmental temperature and pressure and no necessity for the separation and purification of exhausted gas to achieve

high-purity CO_2. Apart from the economic efficiency of the operational conditions, the production of side products and calcium carbonate as the main product made the process economically more recoverable. Table 5 describes the price of the generated products and the estimated amount of their sell. The total pecuniary value of these side and main products was estimated at around 243 $/ ton RM, which can compensate some portion of the initial investments. Moreover, by using RM as a suitable and easy available feed source, the costs regarding transporting the raw material for CCU goals are cut down, thus making the process more economically profitable. Furthermore, 29.4 ton RM is required for capture of 1 ton CO_2.

Table 5. The economic assessment of the products produced during the CCU.

Product	Purity (%)	Price per 1 t product ($)	The amount of obtained product per 1 t RM (kg)	The estimated value ($)
Silica	65	50	53	3
Aluminum	70 -80	110-160	173	23
Hematite	60	200-400	642	193
Calcium carbonate	98	260-300	78.5	24

6. CONCLUSIONS

CCU technologies have been developed as promising techniques in the portfolio of GHG reduction and global warming abatement. In addition to these environmental merits, the acquirement of valuable products during the CCU process is another privilege of this process as it brings about economic recovery to the system. The former merit is highly attended as mitigation of CO_2 emission has become the priority of decision-makers and program managers. Nevertheless, it should be ascertained that GHG mitigation strategies would not bring about other environmental impacts. In this regard, an LCA approach has been employed as a holistic assessment tool to account for all environmental aspects of a product during its life cycle.

This paper studied the environmental impacts of indirect mineral carbonation of CO_2 exhausted from the stacks of Jajarm plant by RM, the alkaline waste of the plant, using LCA guideline. The estimation was carried out by GaBi software under the criteria of ISO 14044 and ISO 14040 in the LCA framework. The result of the climate change category revealed that the emission reduction of about 28.13 kg CO_2 eq/ton RM (around 82 %) can be achieved by the equipment of the conventional process with CCU technology. The carbon footprint calculations based on the PAS 2050 perspective using ISO 14064 showed GHG emission of about 2.33 kg CO_2 eq. According to the mentioned results, achieved for the first time, mineralization of CO_2 released from the flues of Jajarm plant over the mineral residue of the plant is a feasible approach that can be used on a large scale. The outcomes of this work would be highly beneficial for further investigations by researchers since a holistic guideline has been provided here. Further research works can consider the emission of transportation for more accurate analysis. Furthermore, the economic study pointed to the economic recovery of about 243 $/ t RM which is obtainable by the trade of the by- and main-products including silicate, alumina, hematite, and calcium carbonate. The convenient and easy-to-use operational conditions of the process as well as its cost efficiency due to the generation of valuable products can be seen as the greatest merits of this CCU technique.

The LCA-based outcomes suggest that after utilizing CCU in the Jajarm plant for mineral carbonation of RM by CO_2 exhausted from the plant, the emission of GHCs reduced dramatically, which supports the implementation of CCU technology for the real application in Jjarm plant. Additionally, carbon footprint results and economic evaluation confirmed the reduction of GHG emission and showed the promising profitability of the suggested process, which can attract investors to finance this technology.

7. ACKNOWLEDGEMENT

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NOMENCLATURE

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
GHG	Greenhouse Gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
ADP	Abiotic Depletion Potential
ODP	Ozone layer Depletion Potential
HTP	Human Toxicity Potential
FWAETP	Freshwater Aquatic Ecotoxicity Potential
MAETP	Marine Aquatic Ecotoxicity Potential
TEP	Terrestrial Ecotoxicity Potential
POP	Photochemical Oxidation Potential
AP	Acidification Potential
EP	Eutrophication Potential
RM	Red Mud
HCl	Hydrochloric acid

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