Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2026, Volume 14, Issue 4, 1140744

Original Research Article

Integrated Environmental Impact Assessment with Dynamic Life Cycle Assessment Framework for Mineral Carbonation of Steel Slags as a Carbon Capture, Utilization and Storage Technology in Agriculture

Ponnapat Watjanatepin[1*], ***Lola Eelen***[1], ***Laura Steinwidder***[2], ***Nina Miladinović***[3], ***Luka Ceyssens***[3], ***Henning Gösling***[4], ***Christiane Plociennik***[4], ***Tom Van Duyse***[1,5], ***Sara Vicca***[2], ***Tom Van Gerven***[3], ***Martin Ruskowski***[4], ***Karel Van Acker***[1,6,7]

[1] Sustainable Materials Processing and Recycling (SeMPeR), Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, 3001 Leuven, Belgium
e-mail: ponnapat.watjanatepin@kuleuven.be, tom.vanduyse@kuleuven.be, lola.eelen@kuleuven.be, karel.vanacker@kuleuven.be

[2] Biobased Sustainability Engineering (SUSTAIN), Department of Bioscience Engineering, University of Antwerp, Antwerp, Belgium
e-mail: Laura.Steinwidder@uantwerpen.be, sara.vicca@uantwerpen.be

[3] Process Engineering for Sustainable Systems (ProcESS), Department of Chemical Engineering, KU Leuven, Leuven, Belgium
e-mail: anthony.deschutter@kuleuven.be, nina.miladinovic@kuleuven.be, giuseppe.granata@kuleuven.be, tom.vangerven@kuleuven.be

[4] German Research Center for Artificial Intelligence (DFKI), Trippstadter Str. 122, 67663 Kaiserslautern, Germany
e-mail: christiane.plociennik@dfki.de, henning.goesling@dfki.de, martin.ruskowski@dfki.de

[5] Environmental Economics (EnvEcon), Department of Engineering Management, University of Antwerp, Antwerp, Belgium
e-mail: tom.vanduyse@kuleuven.be

[6] Center for Economics and Corporate Sustainability (CEDON), KU Leuven, Warmoesberg 26, BE-1000 Brussels, Belgium
e-mail: karel.vanacker@kuleuven.be

[7] FlandersMake@KU Leuven, Leuven, Belgium
*e-mail: karel.vanacker@kuleuven.be

Cite as: Watjanatepin, P., Eelen, L., Steinwidder, L., Miladinović, N., Ceyssens, L., Gösling, H., Plociennik, C., Van Duyse, T., Vicca, S., Van Gerven, T., Ruskowski, M., Van Acker, K., Integrated Environmental Impact Assessment with Dynamic Life Cycle Assessment Framework for Mineral Carbonation of Steel Slags as a Carbon Capture, Utilization and Storage Technology in Agriculture, J.sustain. dev. energy water environ. syst., 14(4), 1140744, 2026, DOI: https://doi.org/10.13044/j.sdewes.d14.0744

---

[*] Corresponding author

ABSTRACT

Mineral carbonation of steel slags has shown potential as a viable option for carbon capture, utilization, and storage. This process not only valorizes both steel slags and the carbon emissions generated during steel production, but also offers an interesting agricultural application. Carbonated steel slags can serve as substitutes for liming agents or basalt rock powder, and, even when used in agriculture, they continue to capture carbon dioxide throughout their use phase. To ensure that the carbon dioxide captured during the mineral carbonation process exceeds the emissions produced during the mineral carbonation process itself, a life cycle assessment is necessary. This life cycle assessment must incorporate the temporal aspect to monitor emissions and sequestration over time, which is critical for evaluating carbon capture, utilization, and storage technologies. Additionally, including the temporal aspect helps determine whether mineral carbonation is essential, allowing for a comparison between the carbon dioxide captured during both the production (carbonation) and use phases of both carbonated and non-carbonated slags in agriculture. To address this gap, this study proposes an integrated environmental life cycle assessment combined with a dynamic life cycle assessment to track emissions and sequestration over time. This approach enables the visualization of time-dependent radiative forcing and the cumulative carbon dioxide capture throughout both the production and use phases of carbonated slags. The study utilizes empirical data collected from the Research Foundation Flanders funded AgriCarb project. This project includes steel slag carbonation and emission measurements over 435 days to demonstrate the proposed integrated conventional and dynamic life cycle assessment framework. At the time of writing this abstract, no known studies have applied dynamic life cycle assessment to a carbon capture, utilization, and storage case study, making this research novel and the first to demonstrate such a framework in this context. Preliminary results from the assessment show that carbonated slags sequestered more carbon dioxide over the 435-day period, combining sequestration from both the carbonation process and the agricultural use phase, compared to non-carbonated slags. These findings quantitatively demonstrate the environmental benefits of mineral carbonation. This integrated framework offers a practical, quantitative approach to evaluating mineral carbonation of steel slags as a carbon capture, utilization, and storage technology and provides a valuable tool for future assessments of other carbon capture, utilization, and storage technologies.

KEYWORDS

Life Cycle Assessment, Dynamic Life Cycle Assessment, Mineral Carbonation, Steel Slags, Carbon Capture, Utilization and Storage

INTRODUCTION

The demand for raw materials is continually increasing, driven by the need to support population growth, as well as economic and societal development. Iron and steel, as primary materials, play a crucial role in sustaining this growth. However, the production of steel and iron remains one of the most significant anthropogenic sources of carbon emissions [1]. Furthermore, the steel manufacturing process generates approximately 15-25% of steel slag per unit of crude steel, particularly when using basic oxygen and electric arc furnaces [2].

Mineral carbonation offers a potential solution to valorize the two waste streams by utilizing carbon dioxide (CO_2) and steel slag waste streams to produce stable silicates and carbonates [2]. This process involves a chemical reaction between carbon dioxide, hydroxide anions, and metal cations on the surface of an alkaline source, such as steel slag. The reaction forms silicate and carbonate layers on the slag's surface, with water facilitating the dissolution of calcium (Ca) and magnesium (Mg) in the slag to generate metal cations. The mineral carbonation process has the capacity to sequester carbon dioxide stably for millennia [2]. As such, the mineral carbonation of steel slags is categorized as a carbon capture and storage (CCS) technology. Notably, the carbonated slags produced from this process have diverse applications, including in the construction and agricultural sectors, positioning mineral carbonation of steel slags as part of carbon capture, utilization, and storage (CCUS) technologies [3].

The efficiency of the steel slag carbonation process is influenced by several factors, including carbonation duration, temperature, particle size of the steel slags, CO_2 pressure and concentration, and the liquid-to-solid ratio in the reactor, among others [4]. Notably, the CO_2 used in the carbonation process does not require high purity, allowing the use of flue gases with varying CO_2 concentrations from the steel manufacturing process. Therefore, mineral carbonation of steel slags presents a promising approach to simultaneously valorize and create value from two key waste streams of the steel industry: slags and flue gases.

Carbonated slags can be used in different applications [3]. Recent studies reported the use of carbonated slags in construction as substitute materials, for instance to replace ordinary Portland cement, in concrete blocks. Agricultural applications are also another realm of possibility of the application of carbonated slags. Carbonated steel slags have been reported to help improve the soil's water retention property, remediate soil acidification potential and also to provide macro-nutrients to biomass produce. In this manner, mineral carbonation of steel slags can both be used as a carbon capture technology to store carbon emissions stably while being beneficial in agricultural applications to replace conventional comments such as liming agents or macro-nutrients like basalt rock powder. The use of carbonated steel slags in agriculture as a CCUS material is rather novel and still emergent, meaning that limited studies have addressed them.

For a CCUS technology to be considered effective, it must deliver environmental benefits, particularly by achieving a net negative carbon balance. Given that CCUS technologies are frequently energy-intensive, the carbon emissions associated with the carbon capture and storage process should be lower than the amount of CO_2 sequestered. To assess this, a standardized life cycle assessment (LCA) can be employed [5]. LCA is a tool used to quantify the environmental impacts of a system, providing insight into the environmental footprint of the system under investigation [6]. LCA results can be used as an iterative feedback for design improvements, environmental impacts mitigation and recommendations as well as to identify hotspots for iterative modifications of products or technologies. LCA covers a wide range of environmental impact categories, ranging from climate change to ecosystem health to human health to resource use. One important impact category in LCA is the Global Warming Potential (GWP).

One limitation of the conventional life cycle impact assessment methodology for the GWP calculation is that GWP-values are dependent and sensitive to the choice of the time horizon used for the GWP calculation [7]. Firstly, short-lived greenhouse gases (for instance, methane) will exhibit their total greenhouse potential during the years of their emission, while the longer-lived greenhouse gases (for instance, carbon dioxide) will emit their total greenhouse effect over a longer period of time [8]. Therefore, the calculation of the GWP values for the shorter time horizon would result in higher GWP values for the shorter-lived greenhouse gases (GHG).

In other words, the choice of time horizon is equivalent to giving a weighting on the carbon accounting process – hence, giving higher importance to impacts closer in time. Furthermore, if there is carbon storage and/or delayed emission, the emissions that occur after the time horizon considered will be excluded from the time horizon [9]. Consider an example of a building that is built and lasts for 75 years. In this case, the occurred emissions would be captured with the GWP100 time horizon. However, for a system that only starts to emit from year 25 to year 125 or a system where the emissions only start from year 75 to year 175, the GWP100 would not capture the whole emission profile.

Therefore, the temporal aspect is particularly relevant for consideration for long-lived products with active use and/or end-of-life phases, the comparison of scenarios with different temporal profiles, prospective comparative studies, bioenergy carbon credits, forest management scenarios and temporary carbon storage [10]. The limitations of the current life cycle assessment (LCA) framework are particularly significant when applied to the comprehensive evaluation of mineral carbonation of steel slags in agricultural contexts. This process, positioned as a carbon capture, utilization, and storage (CCUS) technology, not only contributes to carbon sequestration but also offers a methodological approach for monitoring and integrating temporal dimensions within CCUS systems [11]. Dynamic Life Cycle Assessment (D-LCA) can provide an interesting approach to capture the emissions and assess the GWP at a fixed time horizon, thereby, avoiding the mismatches of the GWP calculation even if the emissions occur at different time points.

Dynamic Life Cycle Assessment (D-LCA) has emerged as a response to the limitations of traditional, static LCA—particularly its inability to reflect how environmental flows, energy systems, material properties, and carbon dynamics change over time, which can lead to inaccurate or misleading climate-impact results. Static LCA typically treats emissions, energy mixes, and material performance as fixed values, even though real-world systems evolve significantly across decades. This causes important gaps in the current conventional LCA: for example, static approaches undervalue biogenic carbon storage and emission timing in biobased systems, underestimate long-term benefits of grid decarbonization in buildings or electric mobility, and fail to capture degradation or efficiency improvements in technologies over their lifespans.

A summary of a recent literature review is provided in **Table 1** below. D-LCA addresses these gaps by incorporating time-dependent life-cycle inventories, dynamic characterization factors (DCF), prospective scenario modelling, and real-time data integration, allowing climate impacts to be evaluated with temporal accuracy. For instance, Ferrari et al. implement ERP-linked D-LCA to overcome the limitations of static, infrequently updated inventories by enabling real-time environmental monitoring within ceramic manufacturing [12]. In the biobased materials domain, Ghannadzadeh & van der Meer's BBM-LCA framework uses dynamic LCA combined with the AMG soil carbon model to capture the timing of biogenic carbon fluxes and soil carbon processes—something static LCA cannot represent—ultimately producing more accurate climate-impact estimates for PLA production [13]. Similarly, D-LCA in the building sector responds to the critical need to model long-term transformations—such as energy-mix decarbonization targets, technological evolution, building-stock transitions, and changes in occupant behavior—revealed in the systematic review by Slavković and Stephan [14] and the review by Su et al. [15], which document widespread use of scenario modelling, dynamic energy simulations, and time-varying inventories to reflect these evolving conditions. It should be highlighted that no publications yet have applied D-LCA in steel slags mineral carbonation as a CCUS for agricultural use.

A key limitation of the current LCA framework is its inability to represent products whose emission profiles vary dynamically over time, such as carbonated steel slags used as a CCUS strategy in agricultural systems as indicated in the previous paragraph and also iterated by the other studies reviewed within this study. To address this methodological gap, the present study proposes an integrated assessment approach that combines both conventional attributional LCA and dynamic LCA, thereby enabling the explicit consideration of temporally differentiated emission and sequestration patterns across the full life cycle of carbonated steel slags. D-LCA is of particular interest for the steel slags mineral carbonation as a CCUS for agricultural application because throughout the use phase of the carbonated slags in agriculture, the carbonated slags still sequester the carbon dioxide as illustrated in the modelling of Watjanatepin et al. (2025) [16] and pot experiment results of Steinwidder et al. (2025) [17]. In addition to this, D-LCA could also be utilized as an assessment approach to confirm the technological effectiveness of the carbonated steel slags to ensure that the sequestration is higher than the emissions, if any.

Table 1: Literature Review of Recent D-LCA Studies

Title	Authors and Year	Sector	Why is D-LCA Needed?	Tools	Conclusion
Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment	Ferrari, Volpi, Settembre-Blundo, García-Muiña (2021) [12]	Ceramic tile manufacturing	Static LCA lacks real-time data	ERP-linked dynamic LCI + custom DLCA engine + SAP BI	D-LCA automated data flows, enabling real-time monitoring and solving static LCA delays
Combining dynamic life cycle assessment and net ecosystem exchange through the framework of biobased materials and products-life	Ghannadzadeh & van der Meer (2025) [13]	Biobased plastics	Static methods ignore timing of biogenic carbon	BBM-LCA + AMG soil carbon model + DCFs	D-LCA captured timing of biogenic fluxes, avoiding static neutrality errors

cycle assessment (BBM-LCA): application to polylactic acid					
Dynamic life cycle assessment of buildings and building stocks – A review	Slavković & Stephan (2025) [14]	Building sector	Long-term system changes ignored in static LCA	Review of DLCA frameworks (MFA, GIS, DCF)	D-LCA improved long-term realism and reduced misestimation of impacts
Assessment models and dynamic variables for dynamic life cycle assessment of buildings: a review	Su et al. (2021) [15]	Buildings	Static LCA ignores occupant, energy mix, degradation dynamics	Simulations + scenario modelling	D-LCA made temporal variability explicit, correcting misleading static conclusions
From carbon neutral to climate neutral Dynamic life cycle assessment for wood-based panels produced in China	Wang et al. (2022) [18]	Forestry	Static LCA cannot assess timing of biogenic emissions	Forest carbon models + radiative forcing DCFs	D-LCA distinguished carbon vs climate neutrality; improved temporal accuracy
Environmental impacts of battery electric light-duty vehicles using a dynamic life cycle assessment for qatar's transport system (2022 to 2050)	Alishaq et al. (2024) [19]	Transport	Static LCA misses future grid changes & efficiency gains	Prospective ReCiPe DLCA	D-LCA showed BEV benefits depend on decarbonized grids, guiding policy timing
Environmental impact assessment of cascading use	Navare et al. (2022) [20]	Biorefinery	Static LCA ignores delayed emissions &	Dynamic CFs + experimental LCI	D-LCA quantified delayed emissions &

of wood in bio-fuels and bio-chemicals			cascading lifetimes		storage benefits, improving cascade evaluation
Dynamic Versus Static Life Cycle Assessment of Energy Renovation for Residential Buildings	Van de Moortel et al. (2022) [21]	Building renovation	Static LCA ignores future energy mix & heating efficiency changes	Dynamic scenario modelling	D-LCA avoided false conclusions about retrofit benefits and improved forecasting

To this end, this study investigates the research question of how to assess the GWP of steel slags mineral carbonation as a CCUS over both the production and the agricultural use phase and confirm the technological effectiveness of mineral carbonation of steel slags? This study then proposes to assess the full life cycle of mineral carbonation of steel slags in agriculture by employing both the conventional attributional LCA for the production phase and the D-LCA using dynamic life cycle inventory to capture the temporally differentiated profiles of the carbon emission or sequestration during its use phase in agriculture.

In doing so, it would be possible to confirm the technological effectiveness of the technology by accounting for the full life cycle of mineral carbonation of steel slags, specifically to account for the active carbonation during the mineral carbonation of steel slags in a reactor and to account for the passive carbonation during the mineral carbonation of steel slags in agriculture. This means that this study will be focusing on the GWP and the other impact categories are not within the scope of this study. However, it should be noted that when communicating the full life cycle impacts assessment results of this CCUS system, it is essential to assess and report the other environmental impact categories for a comprehensive understanding of the overall environmental implications of the CCUS system as well. The novelty of this study lies in the formulation of an assessment pathway based on Levasseur et al. [9] to account for the dynamic carbon emission and sequestration nature of steel slags mineral carbonation as a CCUS in agriculture which has not been demonstrated before.

This study begins by describing the mineral carbonation scenarios and outlining both the integrated life cycle assessment (LCA) and dynamic life cycle assessment (DLCA) methodologies within the Methods section. Following this, the results of the conventional and dynamic LCA are presented, integrated, and critically examined in the Results and Discussion section. The Discussion further elaborates on key insights derived from the analysis, identifies the limitations of the current study, and proposes directions for future research. This study used data from the Flemish government-funded FWO project AgriCarb for the assessment of mineral carbonation of steel slags in agriculture as a CCUS technology. It serves as a case study of the methodological approach used here, which can be employed to assess the temporally-differentiated GWP of different CCUS technologies.

METHODS

The following methods description section is divided into the case description of the mineral carbonation cases and the approaches taken for the conventional and dynamic life cycle assessment in this study.

Mineral Carbonation Case Description

This study utilizes experimental data from lab-scale mineral carbonation of steel slags conducted at the University of Leuven, Belgium [22] where the setup can be consulted. The lab-scale mass, energy consumption, and yields were then projected to an industrial-scale pilot plant scenario (TRL 6) using upscaling frameworks based on a power law learning curve, which accounts for process efficiency and economies of scale as reported in the previous study of the authors [23]. Further multi-criteria decision analysis for each mineral carbonation of steel slags in agriculture scenario were also assessed and more details on the trade-off between the environmental and economic criteria could also be found in this study [16]. The projected industrial scenarios were designed to match the capacity of the industrial wet mineral carbonation installation studied by Lee et al. [24], with an assumed mineral carbonation capacity of 61.8 tons per day, resulting in the production of 22,557 tons of carbonated steel slags annually [25]. **Figure 1** below illustrates the system boundary of this study from cradle-to-grave.

The study includes four mineral carbonation cases as baseline scenarios, which are further divided into two scenarios involving the carbonation of basic oxygen furnace (BOF) steel slags and two involving the carbonation of argon oxygen decarburization (AOD) steel slags, each with varying carbonation degrees. The key differentiating factor among the scenarios is the degree of carbonation, which is determined by the duration of the carbonation process. Specifically, the BOF T2 case is carried out at 4 bar for 2 hours; and the BOF T3 case is carried out at 4 bar for 91 hours. The AOD T1 case refers to the carbonation of AOD steel slags at 4 bar for 3 hours, while the AOD T2 case involves carbonation at 4 bar for 33 hours. This is tabulated in **Table 2**. For the agricultural use phase, a set of pot experiments were performed over a period of 15-month from June 2022 to August 2023. The experimental design comprised mesocosms with dimensions of 50 cm in diameter and 60 cm in height, each equipped with a leaching system and installed outdoors at the University of Antwerp research facility. Basalt was applied at a rate of 50 t ha^{-1}, while steel slags were applied at a reduced rate of 5 t ha^{-1}, reflecting their comparatively unstable structure and higher weathering potential. During the growing seasons (June–September 2022 and June–August 2023), two maize plants (*Zea mays*) were cultivated in each mesocosm.

Table 2: Mineral Carbonation of Steel Slags Cases

Treatment Case	**Slag Type**	**Carbonation Pressure**	**Carbonation Duration**	**Amount of CO_2 sequestered (per ton carbonated slags)**

BOF T2	BOF	4 bar	2 hours	51.2 kg
BOF T3	BOF	4 bar	91 hours	163.1 kg
AOD T1	AOD	4 bar	3 hours	56.9 kg
AOD T2	AOD	4 bar	33 hours	103.4 kg

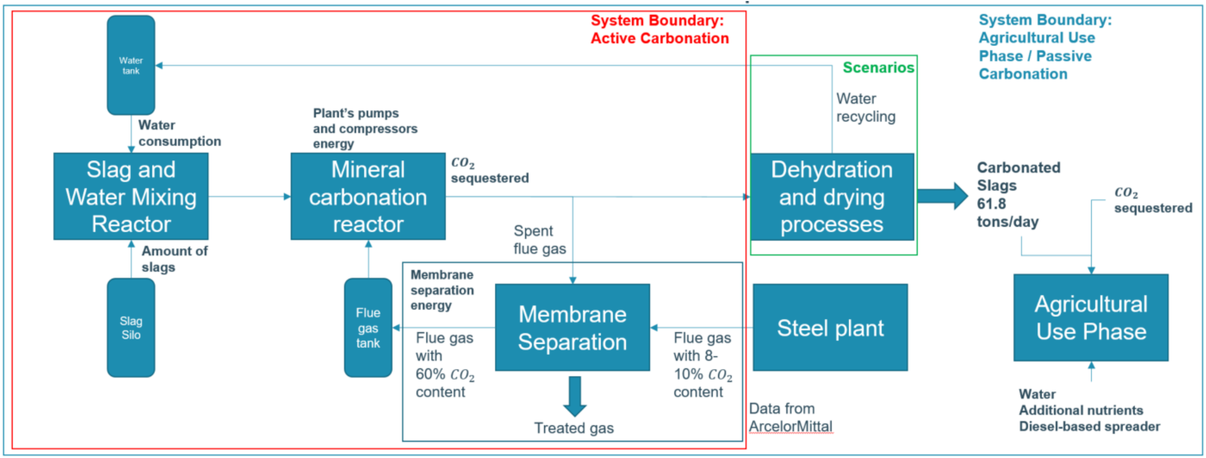

Figure 1: System Boundary of the Mineral Carbonation of Steel Slags as a CCUS in Agriculture Cases

Integrated Conventional and Dynamic Life Cycle Assessment Framework

This section describes the integrated conventional and dynamic life cycle assessment framework that is proposed as an approach to account for the GWP throughout the life cycle of carbonated steel slags as a CCUS in agriculture.

Life Cycle Assessment

The upscaled mass and energy balances of the mineral carbonation process are subsequently applied in the life cycle assessment (LCA) and life cycle costing (LCC) analyses.. The LCA models employed in this study were developed using the Activity Browser in conjunction with the Ecoinvent 3.8 database. The LCA is conducted in compliance with the ISO 14044 standard [5] and follows the guidelines set forth in the ILCD handbook for life cycle assessment [6]. Environmental impacts across all five scenarios are calculated using the Environmental Footprint 3.0 (EF 3.0) methodology, with the functional unit defined as 1 kg of steel slag mineral carbonation at plant capacity, but only the GWP will be presented and used for further investigation according to the scope of this study. Since the mineral carbonation of steel slags is classified as a CCUS technology, the guidelines for LCA from the Global CO_2 Initiative [26, 27] are utilized as a reference. The life cycle inventory (LCI) has been constructed based on the experimental data for both the carbonation phase and the use phase in the Flemish government-funded FWO project AgriCarb. The LCI is provided below in Table 3 based on the previous works of the authors [22, 23]. In this study, the slag is considered burden-free, as it originates from a waste stream within the steel production value chain and therefore carries no upstream environmental burdens. This approach aligns with the objective of the research, which focuses on the valorization of industrial waste streams and consequently treats such materials as free of prior impacts. The captured CO_2 is credited with a value of –1 (modelled as a negative emission to air (hence, sequestration from air) in the biosphere), following the biogenic carbon accounting principles established by the IPCC. This is justified by the fact that the sequestered CO_2 is not expected to be re-emitted and is instead assumed to remain stably immobilized over millennial timescales. A contribution analysis was conducted to identify the principal hotspots within the system. Additionally, a one-at-a-time sensitivity analysis was performed for the global warming potential (GWP) to assess the influence of individual parameters on the overall outcome.

Table 3: Life Cycle Inventory of Steel Slags Mineral Carbonation per day

Inputs (Units)	BOF T2	BOF T3	AOD T1	AOD T2	Data Type
Ground basic oxygen furnace (BOF) or argon-oxygen decarburization (AOD) slags (tons)	61.8	61.8	61.8	61.8	Secondary data from Ecoinvent 3.8
Sequestered CO_2 during mineral carbonation (tons)	3.16	10.01	3.52	6.39	Projected from empirical primary data
Sequestered CO_2 during the agricultural use phase (tons)	0.92	7.98	16.5	15.1	Projected from empirical primary data
Distilled water (tons)	24.72	24.72	24.72	24.72	Secondary data from Ecoinvent 3.8
N-fertilizer (tons)	1.18	1.18	1.18	1.18	Secondary data from Ecoinvent 3.8
P-fertilizer (tons)	0.124	0.124	0.124	0.124	Secondary data from Ecoinvent 3.8
K-fertilizer (tons)	0.494	0.494	0.494	0.494	Secondary data from Ecoinvent 3.8
Energy for membrane separation (MWh)	1.01	3.50	1.22	2.22	Projected from empirical primary data

Plant energy (MWh)	1.52	4.83	1.67	3.07	Projected from empirical primary data
Outputs (Units)					
	BOF T2	BOF T3	AOD T1	AOD T2	
Carbonated steel slags	65.88	79.79	81.82	83,29	

Dynamic Life Cycle Assessment

Dynamic Life Cycle Assessment (D-LCA) analyses the temporal distribution of the emissions by taking into account a dynamic inventory. A one-year time step is utilized and the emission per each greenhouse gas (GHG) i for that one year time step is used for the calculation. The dynamic inventory is combined with dynamic characterization factors (DCF) which can be calculated by using the equation below based on the works of Levasseur et al. [7]:

$$DCF_i(t)_{instantaneous} = \int_{t-1}^{t} a_i[C_i(t)]dt \quad \text{(Equation 1)}$$

Where
DCF = dynamic characterization factor = integral of the radiative forcing for every time step.
a = instantaneous radiative forcing per unit mass of GHG_i in the atmosphere.
C(t) = time-dependent GHG atmospheric load following a unit mass pulse emission.

The sum of the multiplication between the dynamic inventory of each GHG equates to the instantaneous impacts on the radiative forcing (GWI) [7]. The cumulative impact of the radiative forcing can also be calculated by summing up the previous year’s instantaneous impacts up to the time horizon of interest. This can be summarized in the equation below:

$$\text{GWI(t)} = \sum_i GWI_i(t) = \sum_i \sum_{j=0}^{t} ([g_i]_j \cdot [DCF_i]_{t-j}) \quad \text{(Equation 2)}$$

Where
$[g_i]_j$ = inventory result for GHG i at time j

D-LCA enables the calculation of radiative forcing impacts associated with life cycle greenhouse gas (GHG) emissions at any given moment, facilitating the analysis of global warming impacts across scenarios where time is a critical factor. These applications are often associated with scenarios related to temporary carbon storage, gradual carbon sequestration in biomass, and the delay of GHG emissions. Care should be taken in the interpretation of the results as the results of dynamic global warming impact assessments are highly sensitive to the selection of the time horizon [8]. In D-LCA, the evolution of global warming impacts is tracked over time while in conventional LCA, the time horizon is typically chosen prior to conducting the calculations [28].

As previously mentioned, this study utilizes the calculations based on the $DynCO_2$ calculator of Levasseur et al. [8], leading to three types of results being calculated [11]:

1. The instantaneous global warming impact $GWI_{inst}(t)\,[W \cdot m^{-2}]$ represents the radiative forcing resulting from the GHG emissions at any given time t, following the initial time point, which marks the occurrence of the first emission. A positive value indicates that the radiative forcing is higher than it would be without the GHG emissions, while a negative value signifies that the life cycle has a beneficial effect on global warming, reducing the radiative forcing. The instantaneous impact reflects temporal changes in radiative forcing, a capability that is not available when using the conventional Global Warming Potential (GWP).
2. The cumulative global warming impact $GWI_{cum}(t)\,[W \cdot m^{-2}]$ is the sum of all instantaneous impacts from time zero to time t, representing the total additional radiative forcing caused by GHG emissions since the beginning of the life cycle. This cumulative impact enables the comparison of different scenarios and the identification of the scenario with the greatest radiative forcing impact over a given time horizon.
3. The relative impact $GWI_{rel}(t)\ [kg.\ CO_2\ eq.]$ is the ratio of the cumulative life cycle impact to the cumulative impact of a 1 kg CO_2 pulse emission at time zero. This relative impact allows D-LCA results to be expressed in the same units as traditional LCA.

The time horizon applied in this study is derived from the aggregation of daily empirical emissions measurements collected during the pot experiments. These measurements form the basis for the temporal characterization of greenhouse gas (GHG) fluxes over the experimental period.

Although CH_4 and N_2O emissions are relevant—particularly in systems where fertilizers or basalt rock powders are applied, as such conditions can promote microbial processes that generate these gases—the present study is limited by the absence of real-time monitoring capability for these GHGs. At the time the experiments were conducted, no instrumentation was available to quantify CH_4 and N_2O fluxes, and thus their contributions could not be incorporated into the analysis. This point is also further discussed in the limitations as part of the discussion. Future work should address this limitation by integrating appropriate measurement technologies to enable a more comprehensive assessment of total GHG dynamics.

RESULTS AND DISCUSSION

In this part, firstly, the life cycle assessment results of the production phase is shared and discussed. Subsequently, the results from the dynamic life cycle assessment is integrated and described. Finally, the section concluded on several discussion points as well as the limitations and future aspects of the integrated approach performed within this study.

Life Cycle Assessment of the Production Phase

Table 4 below displays the calculated GWP for the four mineral carbonation cases described in **Table 2**. Two non-carbonated steel slags are also displayed for comparison. The column of mineral carbonation – production phase contains the GWP results calculated by the LCA. The LCA was performed on the life cycle inventory shown in **Table 3**. The use phase cases are experimentally measured from the pot experiment and the sequestration rate was calculated based on these empirical results.

According to **Table 4**, BOF T3 carbonation led to the highest sequestration from the active mineral carbonation process. It is also observed that the longer the mineral carbonation process during the production phase leads to higher carbon sequestration. The cases with non-carbonated slags do not have any carbon sequestration in the production phase since they were not carbonated. The GWP impacts observed for the non-carbonated slags cases are due to the energy consumed for the grinding of these slags.

In the second column, the carbon sequestration measured over 435 days from the pot experiments was tabulated and included for the D-LCA. The trend observed is that there are variations in the amount of CO_2 sequestered passively during the agricultural use phase. These uptakes do not express clear trends, however, it is recorded that AOD slags (both carbonated and non-carbonated) led to higher passive carbon sequestration over the 435 days period when compared to the BOF slags.

Based on the sequestration values in the first and second column, the amount of leftover CO_2 sequestration potential (determined by subtracting the sequestered amount in the first and second column with the maximal theoretical uptake limit), the sequestration rate per day based on the 435 days pot-experiment period, the projected yearly sequestration rate per year based on the amount measured during the 435 days pot-experiment period, and the number of years after 435 days to reach the maximal theoretical uptake limit are calculated and displayed for each case in **Table 4** below. It can be observed from **Table 4** that the AOD slags have higher sequestration rate per day during the 435 days pot-experiment period than the BOF slags. This led to the projection that the AOD slags would need between 1 to 2 years after the 435 days period to reach the maximal theoretical uptake if the rates are continuously maintained. BOF slags are projected with a slower carbon sequestration rate, hence, leading to the projection of between 2 to 40 years of continuous carbon sequestration after the 435 days period to reach the maximal theoretical uptake if the rates are continuously maintained. These values were used as inputs for the D-LCA; the results are illustrated in the next section.

Figure 2 presents the contribution analysis associated with the full life cycle of the carbonated slags. **Figure 2** (2A left) illustrates the complete life-cycle profile, encompassing both greenhouse gas emissions and carbon sequestration. In this representation, emissions are shown as positive values, while sequestration is depicted as negative values. For all scenarios, the CO_2 uptake from active carbonation and passive carbonation is indicated in grey and green, respectively. The results demonstrate that extended active carbonation durations also promote increased passive carbonation during the agricultural application phase. **Figure 2** (2B right) isolates only the emission-related contributions to enable clearer identification of the process parameters that dominate the overall impact. Across all cases, plant energy consumption and membrane capture energy emerge as the principal emission hotspots.

Figure 3 also presents the one-at-a-time sensitivity analysis of the global warming potential (GWP) for the selected case of BOF T2. Sensitivity analysis is employed to evaluate how variations in key assumptions or input parameters influence the final output—in this case, the calculated GWP. The BOF T2 scenario is used as a representative example because all analysed cases exhibit similar trends; thus, presenting only one case avoids unnecessary repetition within the study. The results indicate that the most influential parameters are the quantities of carbon dioxide sequestered during both the active mineral carbonation process in the production phase and the passive mineral carbonation occurring during the agricultural application phase. These findings underscore the importance of accurately quantifying CO_2 uptake in future research to ensure reliable GWP assessments.

Table 4: GWP Results of the Production of Carbonated Steel Slags and the Agricultural Use Phase (per kg basis)

Treatment	**Production Phase**	**Agricultural Use Phase**			
	Mineral Carbonation (Production Phase) (kg)	**CO₂ sequestration Day 0-435 (kg/ha)**	Sequestration per day (rate of 0-435) (kg/ha)	Projected sequestration per year (per 365 days) (kg/ha)	Number of years after 435 days
Non-carbonated BOF slags	22.35	-1109.84	2.55	-931.25	2.41
BOF T2	-503.74	-92.445	0.21	-77.57	39.93
BOF T3	-1611.52	-785.76	1.81	-659.32	3.22
Non-carbonated AOD slags	32.35	-1401.21	3.22	-1175.72	2.20
AOD T1	-557.43	-1652.68	3.80	-1386.73	1.49
AOD T2	-1014.53	-1498.89	3.45	-1257.69	1.70

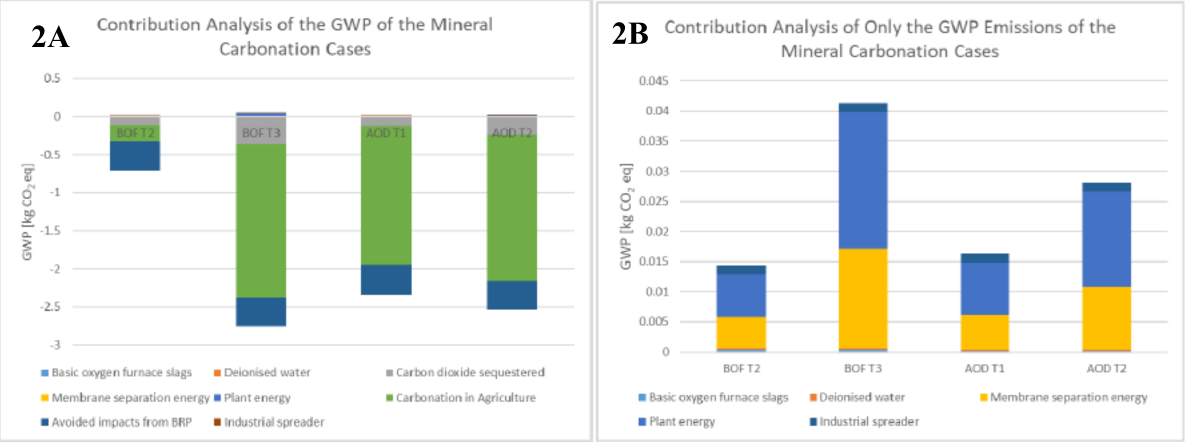

Figure 2: Contribution Analysis of the GWP of the Mineral Carbonation Cases (2A on the left shows the contribution analysis of the GWP of the full life cycle of the mineral carbonation cases and 2B on the right shows the contribution analysis of only the emissions that occur for the full life cycle of the mineral carbonation cases)

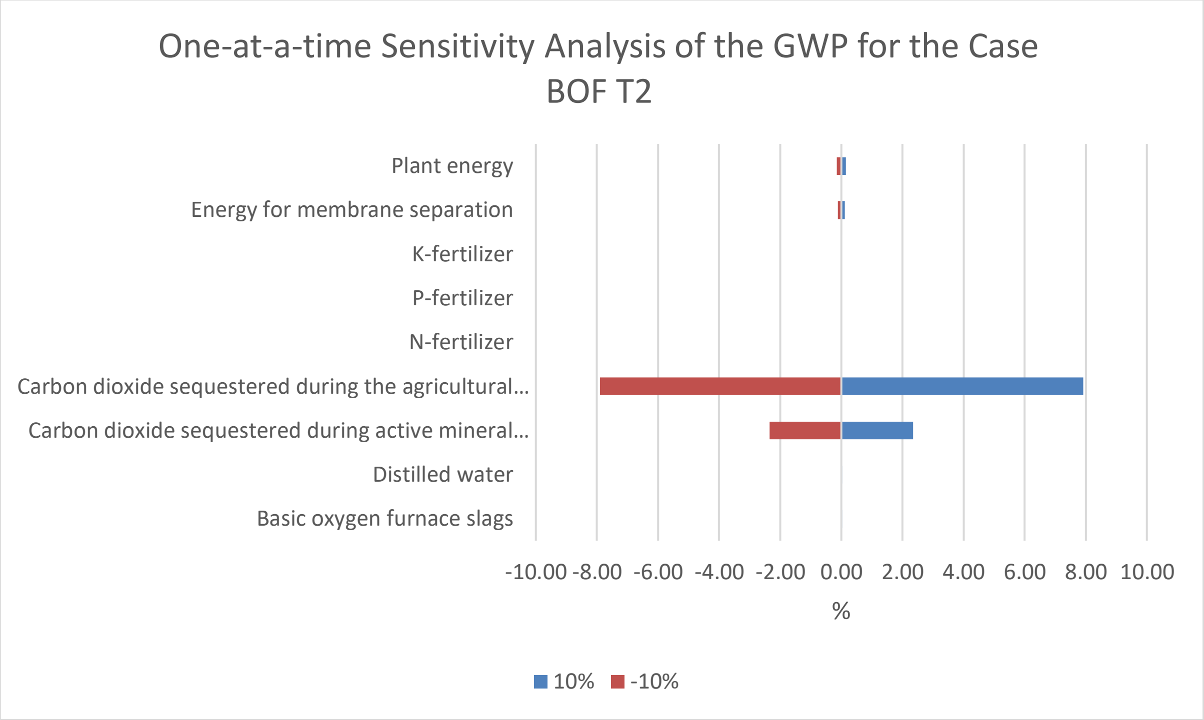

Figure 3: One-at-a-time Sensitivity Analysis of the GWP for the Case of BOF T2

Dynamic Life Cycle Assessment of the Full Life Cycle

Figure 4 below illustrates the instantaneous impacts from the D-LCA for the first set of scenarios focusing on the application of carbonated steel slags in agriculture of up to 435 days of carbon sequestration. The x-axis represents the years (time-step) and the y-axis represents the radiative forcing of the instantaneous impacts in Watt per square metre. The conventional LCA results from the previous section of the active carbonation of the steel slags was combined with the dynamic empirical inventory of the passive mineral carbonation of steel slags during the agricultural use phase. The negative pulse emissions occurred at year 0-1 and peaked at the highest pulse at the end of the second year where the annual pulse radiative forcing is the most negative. After the 435 days period (by the end of the second year), the pulse emission ceased since there is no further uptake as these scenarios assumed that the sequestration only happened up until the experimental period of 435 days, hence, the cessation in the pulse radiative forcing from year 3 onwards. The radiative pulses then proceed towards an equilibrium. It can be observed from the figure that the cases with higher mineral carbonation performed in the production phase resulted in higher negative radiative forcing pulses, considering only the sequestration that occurred in the 435 days period. These cases are AOD T1, BOF T3 and AOD T2 accordingly. These cases also have higher negative radiative forcing pulses than the non-carbonated BOF or AOD slags cases. However, BOF T2 (the case with the shortest carbonation duration) resulted in the lowest negative radiative forcing pulses.

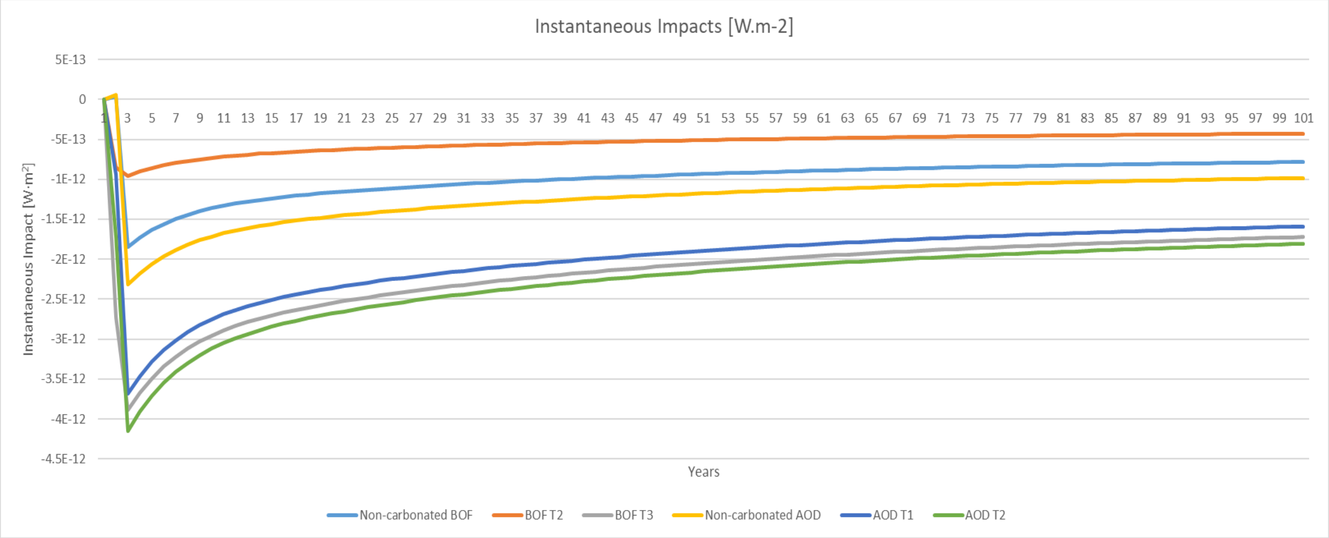

Figure 4: Instantaneous GWP Impacts

Figure 5 and **Figure 6** below illustrate the cumulative and relative impacts of the cases respectively. The x-axis represents the years (time-step) and the y-axis represents the radiative forcing of the instantaneous impacts in Watt per square metre for **Figure 5** and kg of carbon dioxide equivalent in **Figure 6**. The cumulative impact results suggest that the cases with the most carbonation (BOF T3, AOD T1 and AOD T2) resulted in the highest cumulative radiative forcing impacts. Aligning with the graph above, the BOF T3, AOD T1 and AOD T2 resulted in higher cumulative radiative forcing impacts than the non-carbonated BOF and AOD slags. To further clarify the impacts, when the cumulative impacts are translated into relative impacts in **Figure 6** [17], it can be observed that the cases with higher carbonation duration led to higher carbon sequestration over the period of 435 days. The results also suggest that mineral carbonation is needed in order to have higher sequestration during the agricultural use phase since the relative cumulated carbon sequestration is higher in the BOF T3, AOD T1 and AOD T2 cases than the non-carbonated BOF and AOD slags cases. The non-carbonated slags cases did have an emission occurring in year 0-1 due to the grinding processes of the slags. As opposed to the carbonated slags cases, the non-carbonated slags did not have high initial sequestration since they did not undergo the mineral carbonation process. Interestingly, the BOF T2 case did not result in as much carbon sequestration over the 435 days period as the non-carbonated slags cases. This indicates that mineral carbonation is needed up to a certain extent to activate the carbon sequestration potential of the slags so that the slags result in higher sequestration rates over the use phase period. Therefore, further investigation into identifying this trade-off point could provide mineral carbonation technology developers with more information to make informed decisions concerning the duration of the potential mineral carbonation. The principal finding is that longer carbonation durations consistently yield greater net carbon sequestration. This outcome indicates that active carbonation is necessary to enhance the reactivity of steel slags prior to their application in agricultural systems, thereby maximizing their carbon-sequestration potential during the use phase. The integrated conventional and dynamic LCA approach used within this study can provide a guideline for assessing the GWP of products with dynamic emission profiles like carbonated steel slags as a CCUS in agriculture since the emissions throughout the full life cycle could be captured while this would not have been possible with the current LCA framework without the dynamic assessment.

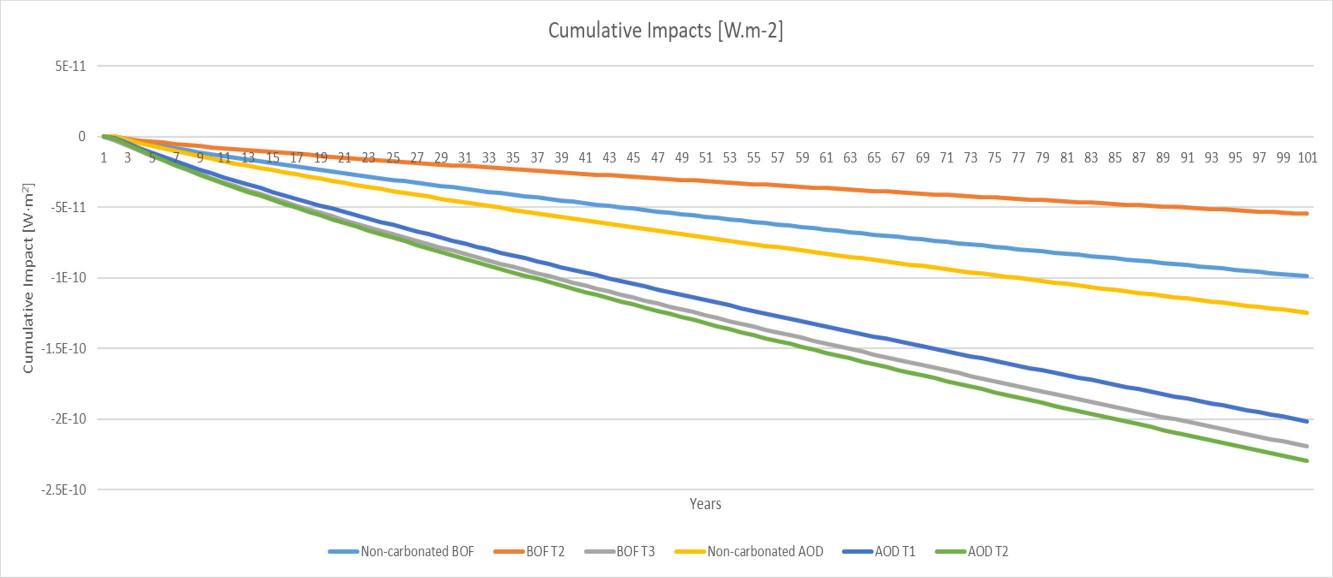

Figure 5: Cumulative GWP Impacts

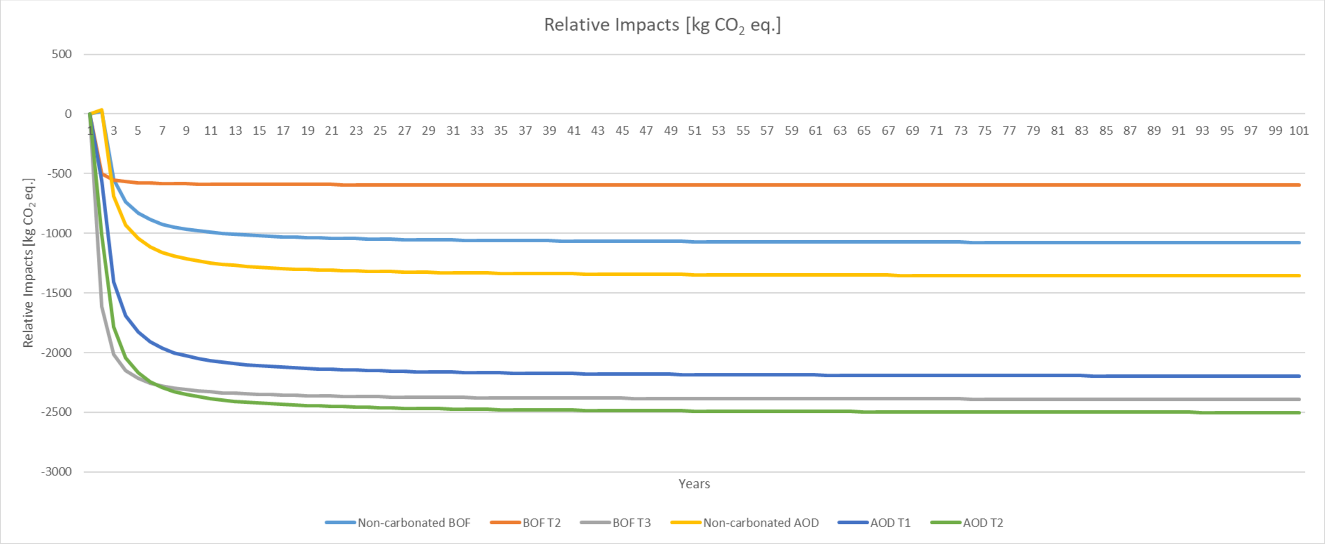

Figure 6: Relative GWP Impacts

Discussion, Limitations and Future Prospects

Due to the limitation of the project's duration, experimental measurements of carbon sequestration were only conducted up to day 435. If the duration had been longer, a more accurate carbonation rate could have been determined. Furthermore, if it were possible to determine the amount of carbonation that occurred after the 435-day agricultural application period, as well as how much carbonation is still remaining, D-LCA could potentially be used to identify whether more carbonation is needed during the production phase in order to establish the optimal trade-off point. One point that needs mentioning is that during the 435-day pot experiment period, all activities are performed by hand. Nonetheless, with the upscaling and the actual use of these slags in agricultural fields, other use phase activities such as the use of an agricultural spreader might also increase the carbon footprint. However, at the time of writing this manuscript, it is not possible to determine this rate, as it is impossible to measure how much carbon the slags have already sequestered. This is because it is difficult to distinguish the carbon sequestration in the slags from that in the soil, as the signals for measurement do not differ between the two. Therefore, a longer duration of the pot experimental setup and/or a model to project or calculate the amount of sequestration potential after the pot-experiment could help to identify the trade-off point between the duration of the mineral carbonation in the production phase and the passive mineral carbonation during the agricultural use phase.

An additional aspect that could be of interest for further study is that as the sequestration of the CO_2 follows Fick's Law of Diffusion, an alternative approach is to project the sequestration rate with a decay curve instead of the current continuous uptake rate. The use of the decay rate could help make the slopes of the carbon sequestration curves more accurate. However, this would not have an impact on the final amount of sequestered CO_2 nor the current conclusions of the findings in this study.

A key limitation of this study is the inability to quantify methane (CH_4) and nitrous oxide (N_2O) emissions during the experimental period. Although these gases are potentially significant—especially in systems amended with fertilizers or basalt rock powders, where microbial activity can generate additional CH_4 and N_2O—real-time monitoring equipment for these GHGs was not available when the pot experiments were conducted. As a result, CH_4 and N_2O fluxes could not be measured or incorporated into the overall greenhouse gas assessment. Future research should integrate appropriate analytical instruments to enable continuous or high-resolution monitoring, thereby providing a more complete evaluation of total GHG dynamics.

Another critical consideration in evaluating the suitability of carbonated steel slags for agricultural use is the potential release of heavy metals or other hazardous substances that could lead to soil or environmental contamination. This issue is particularly relevant given that steel slags, the feedstock for the carbonation process, inherently contain trace metals. Evidence from Steinwidder et al. (2025) [17] indicates that mineral carbonation substantially reduces the mobility of these metals: in their study, carbonated steel slags exhibited no detectable heavy-metal leaching, whereas non-carbonated slags did release measurable quantities. These findings suggest that the carbonation process not only enhances carbon sequestration potential but also contributes to improved environmental safety by stabilizing heavy metals within the slag matrix. Nevertheless, this should be verified on a case-by-case basis, as variations in the chemical composition of steel slags may lead to differing leaching behaviours.Nonetheless, despite these limitations, the current proposed integrated environmental impact assessment of LCA and D-LCA has provided valuable additional insights into the GWP emission profiles of the mineral carbonation of steel slags in agriculture as a CCUS technology. The most important insight is that cases with longer carbonation periods resulted in higher net carbon sequestration. Therefore, it is then advised that active carbonation is needed in order to active these steel slags for to have more carbon sequestration during their agricultural use phase. This integrated assessment was then used to answer the research question mentioned in the introduction of how to assess the GWP for both the production and the use phase of carbonated steel slags in agriculture by employing both the conventional attributional LCA for the production phase and the D-LCA to capture the temporally-differentiated profiles of the carbon emission or sequestration during its use phase to assess the full life cycle of mineral carbonation of steel slags in agriculture.

As future prospects, the use of agentic artificial intelligence (AI) can also help bridge some gaps mentioned and aid in performing D-LCA, taking into account the evaluation of how variations in geographic location, spatial-temporal conditions, and operational parameters influence the environmental impacts of a product system. The autonomous capabilities of AI agents can facilitate continuous monitoring and real-time impact assessment throughout the product lifecycle. By integrating Large Language Models (LLMs) or specialized Small Language Models (SLMs) via the Model Context Protocol (MCP), AI agents can facilitate the acquisition, interpretation, and analysis of dynamic environmental data originating from heterogeneous and temporally variable sources. Furthermore, AI agents can improve the accessibility of LCA results by providing natural language-based interfaces, thereby enhancing communication between technical evaluations and end-users. Within this integrated LCA-D-LCA framework, agentic AI systems can be deployed to monitor the entire value chain of mineral carbonation processes applied to steel slags – from the initial carbonation stage in the reactor to subsequent utilization in agricultural applications. This is particularly relevant if there are human activities in any phase that can be inserted into the calculation based on their natural language-based inputs. During reactor-based carbonation, real-time collection and monitoring of process parameters, material yields, and energy consumption can be carried out. Additionally, greenhouse gas emissions and sequestration metrics can be continuously tracked throughout the process. Integrating these data streams across the value chain facilitates D-LCA, supporting time-dependent evaluation of environmental impacts. Streamlining of data workflows for LCA and LCC has been demonstrated in the work of Zarafshani et al. [29], where life cycle inventories were directly interfaced with the open source Python-based LCA and LCC frameworks to automate the quantification of environmental and economic impacts via the SAB tool. In the study, the SAB tool is streamlined for biorefineries but the methodological application can be for different applications. While this approach significantly improves computational efficiency and reproducibility, it does not incorporate a real-time or dynamic assessment capability. The integration of the LCA–DLCA framework with agentic artificial intelligence has the potential to address this limitation by enabling real-time data processing, adaptive system responses, and continuous impact evaluation. Consequently, the incorporation of agentic AI represents a critical next step and will be a focal point of the author’s future research. A further advancement involves coupling AI-based projections of environmental outcomes with process parameter optimization, thereby enabling ex-ante impact assessments based on the design choices made by technology developers.

CONCLUSION

In this paper, a combined approach of utilizing both the conventional LCA for the active carbonation of steel slags and dynamic LCA for the passive carbonation of steel slags was applied to assess the GWP of steel slags mineral carbonation as a CCUS over both the production and the agricultural use phase and confirm the technological effectiveness of mineral carbonation of steel slags?. This study subsequently proposes assessing the full life cycle of steel-slag mineral carbonation in agricultural applications by combining a conventional attributional LCA for the production stage with a dynamic LCA employing time-resolved inventory data for the use phase. This dual approach enables a more accurate evaluation of the technology’s carbon-mitigation potential by accounting for both active carbonation occurring within the reactor and passive carbonation taking place gradually in agricultural soils. Through this integrated LCA-D-LCA framework, the study captures the temporal dynamics of carbon emissions and sequestration, thereby providing a robust basis for confirming the effectiveness of steel-slag mineral carbonation as a climate-mitigation strategy. The D-LCA results, based on the 435-day emission measurements, indicated that mineral carbonation is needed to enhance carbon sequestration during the agricultural use phase. The carbonated slags resulted in higher carbon sequestration over their full life cycle compared to the non-carbonated slags, except for BOF T2, which suggests that a minimal level of carbonation is necessary for optimizing the carbon sequestration rate during the agricultural use phase. This study also included a projection toward the maximal theoretical carbon sequestration potential, but the results indicated that more data is needed for the D-LCA to clarify the trade-offs between carbon sequestration during mineral carbonation and the use phase. For instance, the amount of carbon sequestered at 435 days should be measured, though this might not be physically feasible. A further consideration is the potential release of heavy metals from steel slags when applied to soils. However, evidences from a separate study showed that mineral carbonation significantly reduces metal mobility: carbonated slags exhibited no detectable heavy-metal leaching, whereas untreated slags did. These findings indicate that carbonation not only enhances carbon sequestration but also improves environmental safety, reinforcing the suitability of carbonated steel slags for agricultural use. Nonetheless, this should be checked in all cases since the composition of the steel slags can be different, resulting in different leaching behaviours. Future studies could focus on this aspect to estimate the rates at which carbon sequestration for each case would level off, which could then be included in the D-LCA. Nonetheless, despite these limitations, the integrated use of the conventional LCA and D-LCA as an assessment tool has provided valuable additional insights into the environmental impact assessments of mineral carbonation of steel slags in agriculture as a CCUS technology.

ACKNOWLEDGMENT

This research was funded by FWO, grant number G0A4821N (Ponnapat Watjanatepin). Laura Steinwidder obtained the FWO fellowship under the grant number 1174923N. The authors would also like to acknowledge the insights obtained through the collaboration with the FWO-funded strategic basic research project – C-Farms.

REFERENCES

[1] J. Gale, J. Bradshaw, Z. Chen, A. Garg, D. Gomez, H. Rogner, D. Simbeck and R. Williams, “Sources of CO2 - IPCC Report,” International Panel on Climate Change, Geneva, Switzerland, 2005.

[2] R. Ragipani, S. Bhattacharya and A. Suresh, “A review on steel slag valorisation: Via mineral carbonation,” *React Chem Eng,* vol. 6, no. 7, pp. 1152-1178, 2021. DOI: 10.1039/d1re00035g

[3] D. Beerling, E. Kantzas and M. Lomas, “Potential for large-scale CO2 removal via enhanced rock weathering with croplands,” *Nature,* vol. 583, no. 7815, pp. 242-248, 2020. DOI: 10.1038/s41586-020-2448-9

[4] C. Woodall, N. McQueen, H. Pilorgé and J. Wilcox, “Utilization of mineral carbonation products: current state and potential,” *Greenh Gases Sci Technol,* vol. 9, no. 6, pp. 1096-1113, 2019. DOI: 10.1002/ghg.1940

[5] A. Baras, J. Li, W. Ni, Z. Hussain and M. Hitch, “Evaluation of Potential Factors Affecting Steel Slag Carbonation,” *Processes,* vol. 11, no. 2590, 2023. https://doi.org/10.3390/pr11092590

[6] ISO, “ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework,” ISO, Geneva, Switzerland, 2006.

[7] L. Zampori and R. Pant, “Suggestions for updating the Product Environmental Footprint (PEF) method,” Publications Office of the European Union, Luxembourg, 2019.

[8] A. Levasseur, P. Lesage, M. Margni, L. Deschenes and R. Samson, “Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments,”

Environ. Sci. Technol., vol. 44, p. 3169–3174, 2010. DOI: 10.1111/j.1530-9290.2012.00503.x

[9] A. Levasseur, P. Lesage, M. Margni, M. Brandao and R. Samson, “Assessing temporary carbon sequestration and storage projects through land use, land-use change and forestry: comparison of dynamic life cycle assessment with ton-year approaches,” *Climatic Change,* vol. 115, p. 759–776, 2012. DOI: 10.1007/s10584-012-0473-x

[10] A. Levasseur, L. P. M. Margni and R. Samson, “Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment,” *Research and Analysis,* 2012. DOI: 10.1111/j.1530-9290.2012.00503.x

[11] M. Brandão, A. Levasseur, M. Kirschbaum, B. Weidema, A. Cowie, S. Jørgensen, M. Hauschild, D. Pennington and K. Chomkhamsri, “Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting,” *The International Journal of Life Cycle Assessment,* pp. 18: 230-240, 2013. DOI: 10.1007/s11367-012-0451-6

[12] A. Levasseur, P. Lesage, M. Margni and R. Samson, “New Generation Carbon Footprinting,” CIRAIG, Montreal, Canada, 2010.

[13] A. Maria Ferrari, L. Volpi, D. Settembre-Blundo and F. E. Garcia-Muina, “Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment,” *Journal of Cleaner Production,* vol. 286, no. 125314, 2021. https://doi.org/10.1016/j.jclepro.2020.125314

[14] A. Ghannadzadeh and Y. van der Meer, “Combining dynamic life cycle assessment and net ecosystem exchange through the framework of biobased materials and products-life cycle assessment (BBM-LCA): application to polylactic acid,” *Biofuels, Bioprod. Bioref.,* vol. 19, p. 1075–1087, 2025.

[15] K. Slavkovic and A. Stephan, “Dynamic life cycle assessment of buildings and building stocks – A review,” *Renewable and Sustainable Energy Reviews,* vol. 212, no. 115262, 2025. https://doi.org/10.1016/j.rser.2024.115262

[16] S. Su, H. Zhang, J. Zuo, X. Li and J. Yuan, “Assessment models and dynamic variables for dynamic life cycle assessment of buildings: a review,” *Environmental Science and Pollution Research,* vol. 28, p. 26199–26214, 2021. https://doi.org/10.1007/s11356-021-13614-1

[17] P. Watjanatepin, L. Steinwidder, A. de Schutter, N. Miladinović, T. Van Duyse, L. Eelen, G. Granata, S. Vicca, T. Van Gerven and K. Van Acker, “Multi-Criteria Decision Analysis of the Environmental and Economic Parameters for Mineral Carbonation of Steel Slags as a Carbon Capture, Utilization and Storage Material,” *Journal of Sustainable Development of Energy, Water and Environment Systems,* vol. 13, no. 2, 2025. https://doi.org/10.13044/j.sdewes.d13.0554

[18] L. Steinwidder, P. L.Boito, J.Frings and e. al., ““Beyond Inorganic C: Soil Organic C as a Key Pathway for Carbon Sequestration in Enhanced Weathering.”,” *Global Change Biology,* vol. 31, no. 7, 2025. https://doi.org/10.1111/gcb.70340.

[19] S. Wang, J. Chen and A. Ter-Mikaelian Michael. Levasseur, “From carbon neutral to climate neutral Dynamic life cycle assessment forwood-based panels produced in China,” *RESEARCH AND ANALYSIS,* vol. 26, p. 1437–1449, 2022. DOI: 10.1111/jiec.13286

[20] A. Alishaq, J. Cooper, J. Woods and O. Mwabonje, “Environmental impacts of battery electric light-duty vehicles using a dynamic life cycle assessment for qatar’s transport system (2022 to 2050),” *The International Journal of Life Cycle Assessment,* vol. 30, p. 110–120, 2025. https://doi.org/10.1007/s11367-024-02381-z

[21] K. Navare, W. Arts, G. Faraca, G. Van den Bossche, B. Sels and K. Van Acker, “Environmental impact assessment of cascading use of wood in bio-fuels and bio-

chemicals," *Resources, Conservation & Recycling,* vol. 186, no. 106588, 2022. https://doi.org/10.1016/j.resconrec.2022.106588

[22] E. Van de Moortel, K. Allacker, F. De Troyer, E. Schoofs and L. Stijnen, "Dynamic Versus Static Life Cycle Assessment of Energy Renovation for Residential Buildings," *Sustainability,* vol. 14, no. 6838, 2022,. https://doi.org/10.3390/su14116838

[23] P. Watjanatepin, L. Steinwidder, A. de Schutter, G. Granata, S. Vicca, T. Van Gerven and K. Van Acker, "Preliminary Environmental Assessment of Carbonated Slags as a Carbon Capture, Utilization and Storage Materials (CCUS)," *Mater. Proc,* vol. 15, no. 1, p. 36, 2023. DOI: 10.3390/materproc2023015036

[24] P. Watjanatepin, L. Steinwidder, A. de Schutter, G. Granata, S. Vicca, T. Van Gerven and K. Van Acker, "Preliminary Environmental and Economic Assessment of Mineral Carbonation of Steel Slags as a Carbon Capture, Utilization and Storage Technology," *CIRP Procedia,* vol. 122, no. 2024, pp. 318-323, 2024. DOI: 10.1016/j.procir.2024.01.047

[25] B. Lee, L. J. Il, Y. Sy, B. Hwang, C. Lim and Y. Park, "Methodology to calculate the CO2 emission reduction at the coal-fired power plant: CO2 capture and utilization applying technology of mineral carbonation," *Sustain,* vol. 12, no. 18, 2020. DOI: 10.3390/SU1218740

[26] H. Lee, T. Kim and S. Kim, "Carbon Dioxide Capture and Product Characteristics Using Steel Slag in a Mineral Carbonation Plant," *Processes,* vol. 11, no. 6, pp. 1-11, 2023. DOI: 10.3390/pr11061676

[27] L. Müller, A. Kätelhön, M. Bachmann, A. Zimmermann, A. Sternberg and A. Bardow, "A Guideline for Life Cycle Assessment of Carbon Capture and Utilization," *Front Energy Res,* vol. 8, no. 2, pp. 1-20, 2020. DOI: 10.3390/pr11061676

[28] V. Sick, "The Need for and Path to Harmonized Life Cycle Assessment and Techno-Economic Assessment for Carbon Dioxide Capture and Utilization," *Energy Technol,* pp. 8, 1901034, 2020. https://doi.org/10.1002/ente.201901034

[29] A. Di Maria, A. Levasseur and K. Van Acker, "Assessing the long term effects on climate change of metallurgical slags valorization as construction material: a comparison between static and dynamic global warming impacts," *Clean Technologies and Recycling,* vol. 1, no. 1, p. 88–111, 2021. DOI: 10.3934/ctr.2021005

[30] H. Zarafshani, P. Watjanatepin, K. Navare, G. Sauve and K. Van Acker, "SAB: An open-access Python-based integrated platform for fully automated emergent sustainability assessment of biorefineries," *Int J Life Cycle Assess,* vol. 29, p. 632–65, 2024. https://doi.org/10.1007/s11367-023-02271-w