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Original Research Article

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

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ABSTRACT

Mineral carbonation of steel slags has shown potential as a viable option for carbon capture, utilisation, and storage. This process not only valorises 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 generated by the process, a life-cycle assessment is necessary. This life-cycle assessment must incorporate the temporal aspects to monitor emissions and sequestration over time, which is critical for evaluating carbon capture, utilisation, and storage technologies. Additionally, including the temporal aspect helps determine whether mineral carbonation is essential, allowing comparison of 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 visualisation of time-dependent radiative forcing and the cumulative carbon dioxide capture throughout both the production and use phases of carbonated slags. The study utilises empirical data collected from the AgriCarb project, funded by the Research Foundation Flanders. This project includes steel slag carbonation and emissions 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, utilisation, 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 days, combining sequestration from both the carbonation process and the agricultural use phase, compared to non-carbonated slags. The 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, utilisation, and storage technology and provides a valuable tool for future assessments of other technologies in these fields.

KEYWORDS

Life Cycle Assessment; Dynamic Life Cycle Assessment; Mineral carbonation; Steel slags; Carbon Capture, Utilisation and Storage.

INTRODUCTION

The demand for raw materials is continually increasing, driven by the need to support population growth and 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 valorise the two waste streams by utilising carbon dioxide (CO_2) and steel slag to produce stable carbonates and silicates [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, generating metal cations. The mineral carbonation process can sequester carbon dioxide stably for millennia [2]. As such, the mineral carbonation of steel slags is categorised as a carbon capture and storage (CCS) technology. Notably, the carbonated slags produced from this process have diverse applications, including in construction and agricultural sectors, positioning mineral carbonation of steel slags as part of carbon capture, utilisation, 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 valorise 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 another potential use for carbonated slags. Carbonated steel slags have been reported to improve the soil's water retention property, remediate soil acidification potential and also to provide macro-nutrients to biomass production. In this manner, mineral carbonation of steel slags can both be used as a carbon capture technology to stably store carbon emissions and be beneficial in agricultural applications, replacing conventional amendments 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 emerging, so 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 standardised life cycle assessment (LCA) can be employed [5]. LCA is a tool used to quantify the environmental impacts of a system, providing insight into its environmental footprint [6]. LCA results can be used for iterative feedback on design improvements, environmental impact mitigation, and recommendations, as well as to identify hotspots for iterative modifications to products or technologies. LCA covers a wide range of environmental impact categories, including climate change, ecosystem health, human health, and resource use. One important impact category in LCA is the Global Warming Potential (GWP).

A limitation of the conventional life-cycle impact assessment methodology for GWP calculation is that GWP values depend on and are sensitive to the time horizon used [7]. Firstly, short-lived greenhouse gases (for instance, methane) will exert their full greenhouse potential during the years of their emissions, while longer-lived greenhouse gases (for instance, carbon dioxide) will emit their total greenhouse effect over a longer period [8]. Therefore, calculating GWP values over a shorter time horizon would yield higher GWP values for the shorter-lived greenhouse gases (GHGs).

In other words, the choice of time horizon is equivalent to assigning 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 emitted amounts would be captured using the GWP100 time horizon. However, for a system that only starts to emit from year 25 to year 125 or a system where 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 the consideration of 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, utilisation, 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 emissions and assess the GWP over a fixed time horizon, thereby avoiding 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 creates significant gaps in conventional LCA: for example, static approaches undervalue biogenic carbon storage and the timing of emissions in biobased systems, underestimate the long-term benefits of grid decarbonisation 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**. D-LCA addresses these gaps by incorporating time-dependent life-cycle inventories, dynamic characterisation 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 decarbonisation targets, technological evolution, building-stock transitions, and changes in occupant behaviour, 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 noted that no publications have yet applied D-LCA to mineral carbonation of steel slags 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 reiterated 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, D-LCA could be used as an assessment approach to confirm the technological effectiveness of carbonated steel slags and ensure that sequestration exceeds any emissions, if any.

To this end, this study investigates the research question of how to assess the GWP of steel slag mineral carbonation as a CCUS across both the production and agricultural use phases, and to confirm its technological effectiveness. 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 approach means the study will focus on the GWP, with the other impact categories outside its scope.

Table 1. Literature review of recent D-LCA studies

Author and year	Sector	Why is D-LCA needed?	Tools	Conclusion
Ferrari *et al.* (2021) [12]	Ceramic tile manufact-uring	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
Ghannadzadeh & van der Meer (2025) [13]	Biobased plastics	Static methods ignore timing of biogenic carbon	BBM-LCA + AMG soil carbon model	D-LCA captured timing of biogenic fluxes, avoiding

Author and year	Sector	Why is D-LCA needed?	Tools	Conclusion
			+ DCFs	static neutrality errors
Slavković & Stephan (2025) [14]	Building sector	Long-term system changes ignored in static LCA	Review of DLCA frame-works (MFA, GIS, DCF)	D-LCA improved long-term realism and reduced misestimation of impacts
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
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
Alishaq *et al.* (2024) [19]	Transport	Static LCA misses future grid changes & efficiency gains	Prospective ReCiPe DLCA	D-LCA showed BEV benefits depend on decarbonised grids, guiding policy timing
Navare *et al.* (2022) [20]	Biorefinery	Static LCA ignores delayed emissions & cascading lifetimes	Dynamic CFs + experimental LCI	D-LCA quantified delayed emissions & storage benefits, improving cascade evaluation
Van de Moortel *et al.* (2022) [21]	Building renovation	Static LCA ignores future energy mix & heating effi-ciency changes	Dynamic scenario modelling	D-LCA avoided false conclusions about retrofit benefits and improved forecasting

However, it should be noted that when communicating the full life-cycle impact assessment results of this CCUS system, it is essential to assess and report on other environmental impact categories to provide a comprehensive understanding of the system's overall environmental implications. The novelty of this study lies in the formulation of an assessment pathway based on Levasseur *et al.* [9], to account for the dynamic nature of carbon emissions and the sequestration potential 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 to assess the 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 utilises 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 authors' previous study [23]. Further multi-criteria decision analysis for each mineral carbonation of steel slags in the agricultural scenario was also conducted, and more details on the trade-off between environmental and economic criteria can be found in [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 t per day, resulting in the production of 22,557 t of carbonated steel slags annually [25]. Figure 1 illustrates the system boundary of this study from cradle to grave.

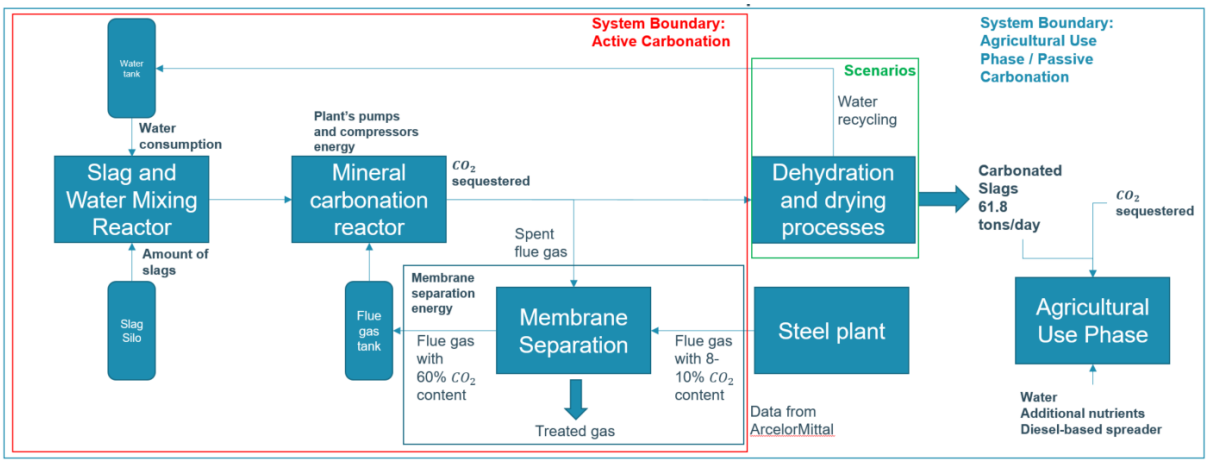

Figure 1. System boundary of the mineral carbonation of steel slags as a CCUS in agriculture cases

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 decarburisation (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 performed at 4 bar for 2 h, and the BOF T3 case at 4 bar for 91 h. The AOD T1 case refers to the carbonation of AOD steel slags at 4 bar for 3 h, while the AOD T2 case – carbonation at 4 bar for 33 h. Table 2 shows the basic data of all cases.

Table 2. Mineral carbonation of steel slag cases

Treatment case	Slag type	Carbonation pressure	Carbonation duration	CO_2 sequestered (per 1 t carbonated slag)
BOF T2	BOF	4 bar	2 h	51.2 kg
BOF T3	BOF	4 bar	91 h	163.1 kg
AOD T1	AOD	4 bar	3 h	56.9 kg
AOD T2	AOD	4 bar	33 h	103.4 kg

For the agricultural use phase, a set of pot experiments was performed over 15 months from June 2022 to August 2023. The experimental design comprised mesocosms measuring 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.

Integrated Conventional and Dynamic Life Cycle Assessment Framework

This section describes the integrated conventional and dynamic life cycle assessment framework proposed to account for the GWP throughout the life cycle of carbonated steel slags used for 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 used in this study were developed in the Activity Browser using the Ecoinvent 3.8 database. The LCA is conducted in accordance with ISO 14044 [5] and follows the guidelines outlined 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. 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, LCA guidelines from the Global CO_2 Initiative [26, 27] are utilised 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 in **Table 3** based on the authors' previous work [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 research objective, which focuses on the valorisation 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 the air, i.e., sequestration from the air, in the biosphere), following the biogenic carbon accounting principles established by the IPCC. This approach is justified by the fact that the sequestered CO_2 is not expected to be re-emitted and is instead assumed to remain stably immobilised over millennial timescales. A contribution analysis was conducted to identify the system's principal hotspots. Additionally, a one-at-a-time sensitivity analysis of the global warming potential (GWP) was performed to assess the influence of individual parameters on the overall outcome.

Table 3. Life Cycle Inventory of steel slag mineral carbonation per day

Inputs	BOF T2	BOF T3	AOD T1	AOD T2	Data type
Ground basic oxygen furnace (BOF) or argon-oxygen decarburisation (AOD) slags [t]	61.8	61.8	61.8	61.8	Secondary data from Ecoinvent 3.8
Sequestered CO_2 during mineral carbonation [t]	3.16	10.01	3.52	6.39	Projected from empirical primary data
Sequestered CO_2 during the agricultural use phase [t]	0.92	7.98	16.5	15.1	Projected from empirical primary data
Distilled water [t]	24.72	24.72	24.72	24.72	Secondary data from Ecoinvent 3.8
N-fertiliser [t]	1.18	1.18	1.18	1.18	Secondary data from Ecoinvent 3.8
P-fertiliser [t]	0.124	0.124	0.124	0.124	Secondary data from Ecoinvent 3.8
K-fertiliser [t]	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	BOF T2	BOF T3	AOD T1	AOD T2	
Carbonated steel slags [t]	65.88	79.79	81.82	83.29	

Dynamic Life Cycle Assessment. Known under the acronym D-LCA, it analyses the temporal distribution of emissions by accounting for a dynamic inventory. A one-year time step is utilised, and the emission per i-th greenhouse gas (GHG_i) for that time step is used for the calculation. The dynamic inventory is combined with dynamic characterisation factors (DCF), which can be calculated by using the equation below based on the works of Levasseur *et al*. [7]:

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

where: DCF_i denotes the dynamic characterisation factor, the integral of the radiative forcing for every time step; a_i – instantaneous radiative forcing per unit mass of GHG_i in the atmosphere; $C_i(t)$ – time-dependent GHG_i atmospheric load following a unit mass pulse emission.

The sum of the products between the DCF_i and inventory result of each GHG_i equates to the instantaneous impact on the radiative forcing (GWI) [7]. The cumulative impact of the radiative forcing can be calculated by summing up the previous year's instantaneous impacts up to the time horizon of interest, as summarised in eq. (2):

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

where $[g_i]_j$ denotes the 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 interpreting the results, as 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, whereas in conventional LCA, the time horizon is typically set before the calculations [28].

As previously mentioned, this study utilises 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 in the absence of GHG emissions. In contrast, a negative value indicates that the life cycle has a beneficial effect on global warming, thereby reducing radiative forcing. The instantaneous impact reflects temporal changes in radiative forcing, a capability 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 comparing different scenarios and identifying the one with the greatest radiative forcing 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 used in this study is derived from aggregating daily empirical emissions measurements collected during the pot experiments. These measurements form the basis for the temporal characterisation of greenhouse gas (GHG) fluxes over the experimental period.

Although CH_4 and N_2O emissions are relevant – particularly in systems where fertilisers or basalt rock powders are applied, which promote microbial processes that generate such emissions, the present study is limited by the absence of real-time monitoring capability for these two 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 elaborated in the discussion and limitations section. 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 section, the life-cycle assessment results for the production phase are presented and discussed first. Subsequently, the results from the dynamic life cycle assessment are integrated and described. The section concludes with several discussion points as well as the limitations and future directions of the integrated approach used in 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 measured experimentally in the pot experiment, and the sequestration rate is calculated from the empirical results.

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]	CO_2 sequestration, days 0–435 [kg ha^{-1}]	Sequestration per day (rate of days 0–435) [kg ha^{-1}]	Projected sequestration per year (365 days) [kg ha^{-1}]	Number of years after 435 days
Non-carbonated BOF slags	22.35		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	–1109.84	3.80	–1386.73	1.49
AOD T2	–1014.53	–1498.89	3.45	–1257.69	1.70

According to Table 4, BOF T3 carbonation resulted in the highest sequestration in the active mineral carbonation process. It is also observed that the longer the mineral carbonation process during the production phase, the higher the carbon sequestration. The cases with non-carbonated slags do not involve carbon sequestration during production, since they were not carbonated. The GWP impacts observed for the non-carbonated slags cases are due to the energy required to grind these slags.

In the second column of the results, 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 show clear trends; however, it is recorded that AOD slags (both carbonated and non-carbonated) led to higher passive carbon sequestration over the 435-day period compared to BOF slags.

Based on the sequestration values in the first and second column of the results, 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. It can be observed that the AOD slags have a higher sequestration rate per day during the 435 days of the pot experiment than the BOF slags. This led to the projection that the AOD slags would need between 1 and 2 years after the 435 days to reach the maximal theoretical uptake if the rates are continuously maintained. BOF slags are projected to have a slower carbon sequestration rate, leading to a range of 2 to 40 years of continuous carbon sequestration after the 435 days required 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 for the full life cycle of the carbonated slags. **Figure 2a** 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, CO_2 uptake from active and passive carbonation is shown in grey and green, respectively. The results demonstrate that extended active carbonation durations also promote increased passive carbonation during the agricultural application phase.

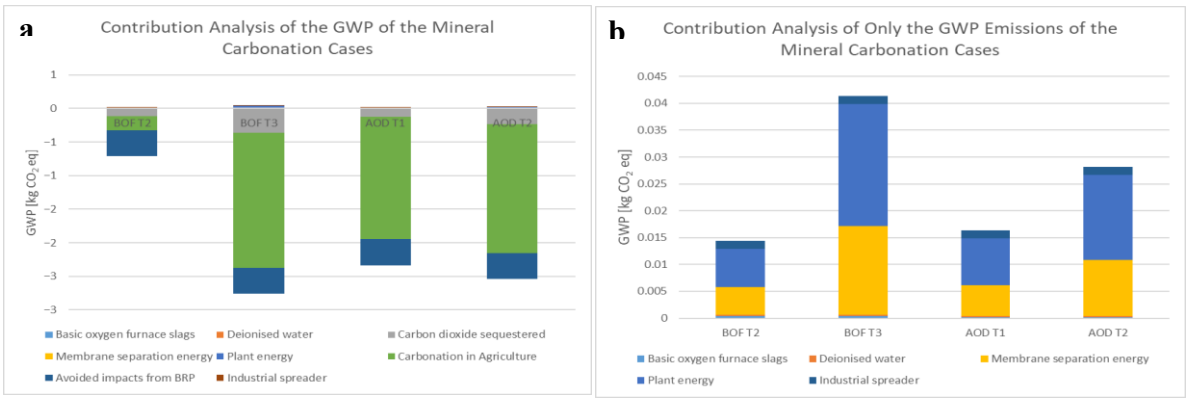

Figure 2. Contribution analysis of the GWP of the mineral carbonation: full life cycle of the mineralcarbonation cases (a) and only the emissions that occur for the full life cycle of the mineral carbonation cases (b)

Figure 2b isolates only the emission-related contributions, enabling 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 presents the one-at-a-time sensitivity analysis of the global warming potential (GWP) for the selected BOF T2 case. 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.

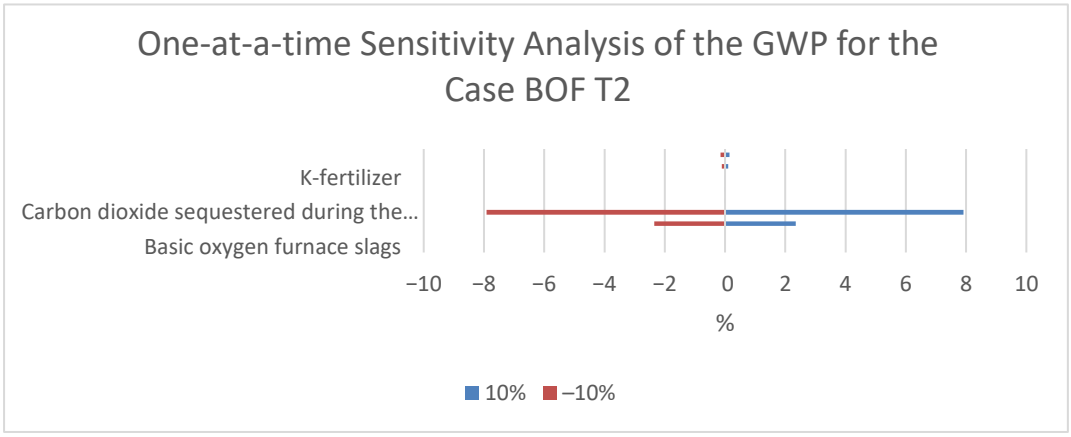

Figure 3. One-at-a-time sensitivity analysis of the GWP for the case of BOF T2

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, with up to 435 days of carbon sequestration. The x-axis represents the years (time steps), and the y-axis represents the radiative forcing of the instantaneous impacts [Wm^{-2}].

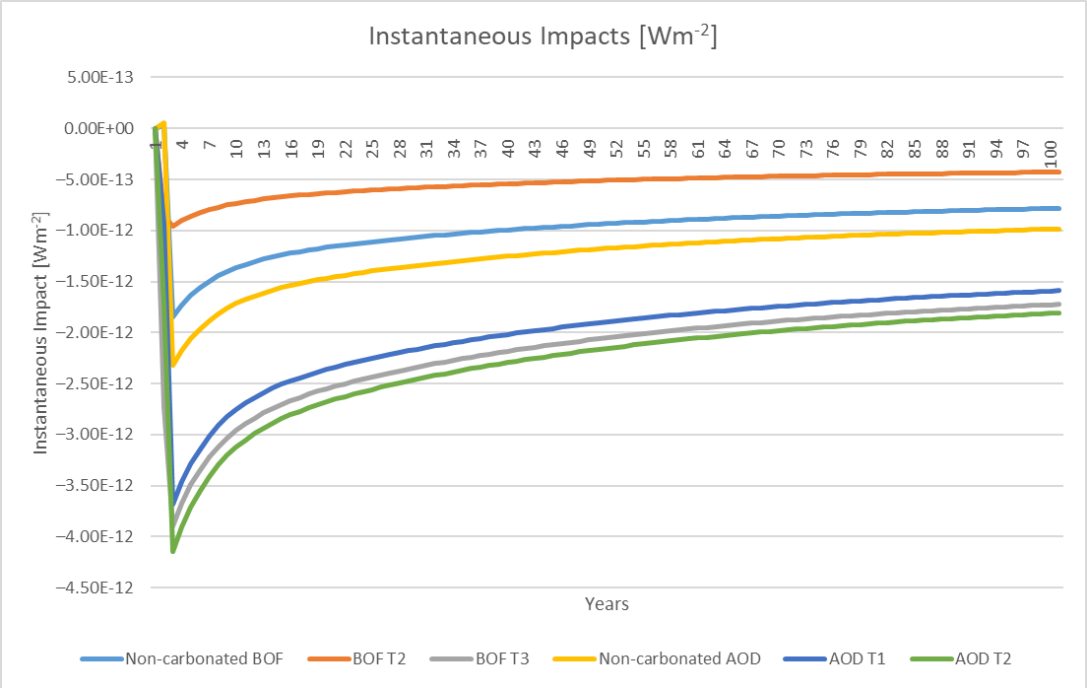

Figure 4. Instantaneous GWP impacts

The conventional LCA results for the active carbonation of steel slags, from the previous section, were combined with the dynamic empirical inventory of the passive mineral carbonation of steel slags during the agricultural use phase. Negative pulse emissions occurred in year 0–1 and peaked at the highest pulse at the end of the second year, where the annual pulse radiative forcing is most negative. After the 435 days (by the end of the second year), pulse emission ceased because there was no further uptake. These scenarios assumed that sequestration occurred only up to the 435-day experimental period; hence, the cessation of pulse radiative forcing from year 3 onwards. The radiative pulses then proceed towards an equilibrium. As shown in the figure, cases with higher mineral carbonation during the production phase resulted in larger negative radiative forcing pulses, considering only the sequestration that occurred over the 435 days. These cases are AOD T1, BOF T3, and AOD T2, having 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.

Further, Figure 5 and Figure 6 illustrate the cumulative and relative impacts of the cases, respectively. The x-axis represents the years (time steps), and the y-axis represents the radiative forcing of the instantaneous impacts in [Wm^{-2}] for Figure 5 and [kg CO_2eq.] for 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. Aligning with the graph in Figure 5, 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 cases with longer carbonation duration led to higher carbon sequestration over 435 days.

The results also suggest that mineral carbonation is needed to achieve higher sequestration during the agricultural use phase, as the relative cumulative carbon sequestration is higher in the BOF T3, AOD T1, and AOD T2 cases than in the non-carbonated BOF and AOD slags cases. The non-carbonated slag cases did have emissions in year 0–1 due to the grinding of the slags. In contrast to carbonated slags, non-carbonated slags did not exhibit high initial sequestration because they did not undergo the mineral carbonation process.

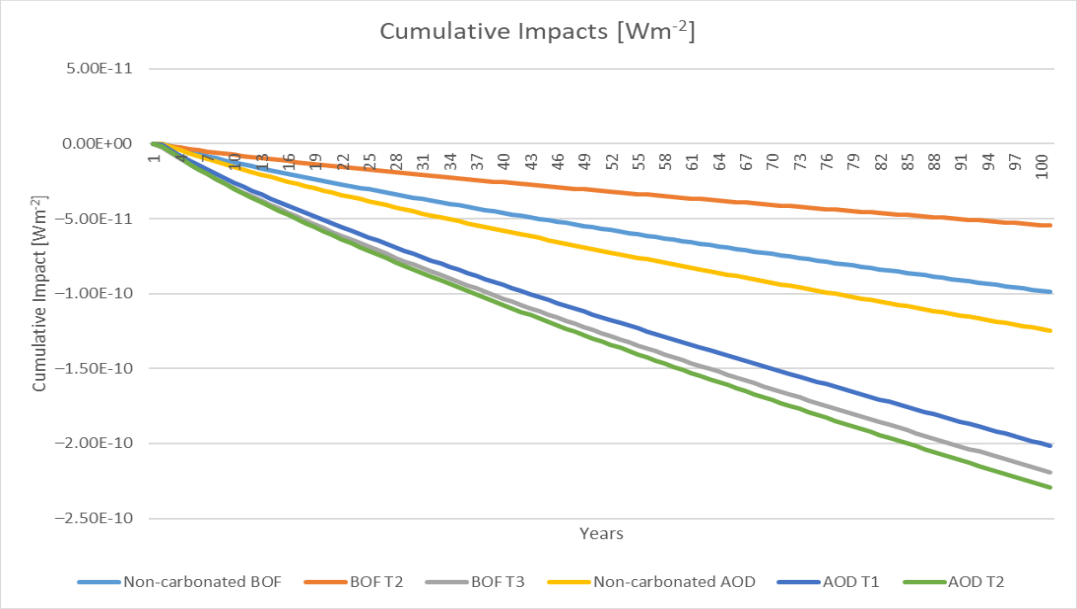

Figure 5. Cumulative GWP impacts

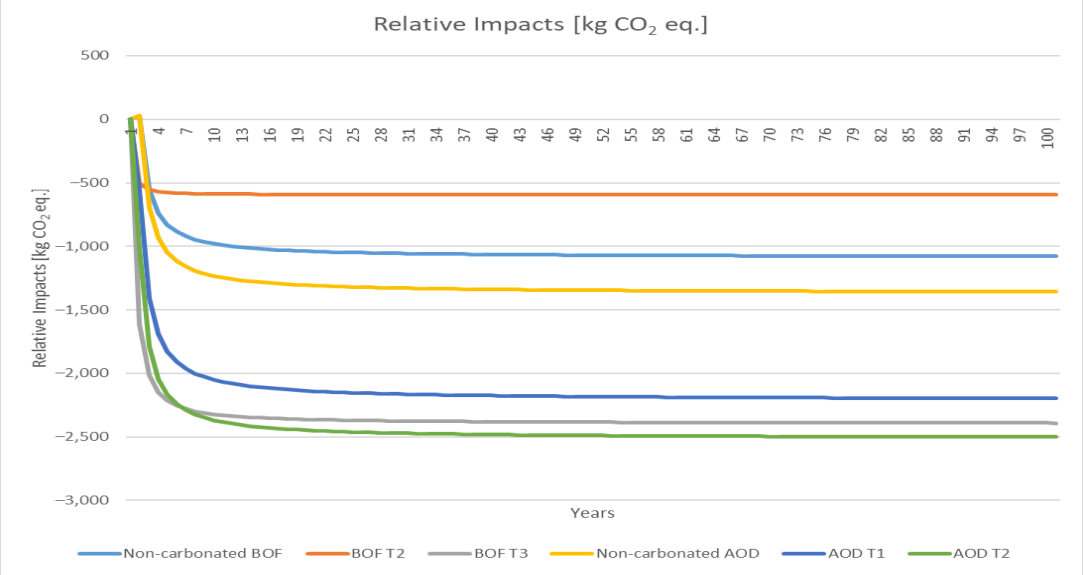

Figure 6. Relative GWP impacts

Interestingly, the BOF T2 case did not result in as much carbon sequestration over the 435-day period as the non-carbonated slags cases. This indicates that mineral carbonation is needed to a certain extent to activate the carbon sequestration potential of the slags, resulting in higher sequestration rates during the use phase. Therefore, further investigation into identifying this trade-off point could provide mineral carbonation technology developers with more information to support decisions about the duration of 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 before their application in agricultural systems, thereby maximising their carbon-sequestration potential during use. 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, which would not have been possible with the current LCA framework without the dynamic assessment.

Discussion, Limitations and Prospects

Due to the project's limited duration, experimental measurements of carbon sequestration were conducted only 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 the amount still remaining, D-LCA could potentially be used to identify whether more carbonation is needed during the production phase to establish the optimal trade-off point. One circumstance to mention is that during the 435-day pot experiment period, all activities are performed by hand. Nonetheless, with upscaling and the actual use of these slags in agricultural fields, other use-phase activities, such as spreading them with 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, due to the difficulty in distinguishing carbon sequestration in slags from that in soil, as the measurement signals do not differ between the two. Therefore, a longer pot experiment duration and/or a model to project or calculate sequestration potential after the pot experiment could help identify the trade-off between the duration of mineral carbonation in the production phase and passive mineral carbonation during the agricultural use phase.

An additional aspect that could be of interest for further study is that, as CO_2 sequestration follows Fick's Law of Diffusion, an alternative approach is to project the sequestration rate using a decay curve rather than the current continuous uptake rate. Using the decay rate could improve the accuracy of the slopes of the carbon sequestration curves. 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 fertilisers 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 during the pot experiments. 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 contaminate soil or the environment. This issue is particularly relevant given that steel slags, the feedstock for the carbonation process, inherently contain trace metals. Evidence from Steinwidder *et al.* [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 improves environmental safety by stabilising 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.

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 advised that active carbonation is needed to activate these steel slags and increase 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 of the gaps mentioned and aid in performing D-LCA, taking into account 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 life cycle. By integrating Large Language Models (LLMs) or specialised 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 temporally variable sources. Furthermore, AI agents can improve the accessibility of LCA results by providing natural-language interfaces, thereby enhancing communication between technical evaluators 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 utilisation in agricultural applications. This approach is particularly relevant if there are human activities in any phase that can be incorporated 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 are possible.

Additionally, GHG 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 by Zarafshani *et al.* [29], who interfaced life-cycle inventories with 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 approach can be applied to other contexts. 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 optimisation, thereby enabling ex-ante impact assessments based on the design choices made by technology developers.

CONCLUSIONS

In this paper, a combined approach of utilising 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 proposed 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 within the reactor and passive carbonation occurring gradually in agricultural soils. Through this integrated LCA-D-LCA framework, the study captured 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 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 than the non-carbonated slags, except for BOF T2, suggesting that a minimal level of carbonation is necessary to optimise the carbon sequestration rate during the agricultural use phase. This study also included a projection toward the maximal theoretical carbon sequestration potential. Still, the results indicated that more data are needed for the D-LCA to clarify the trade-offs between carbon sequestration during mineral carbonation and during 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, evidence 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, it should be checked in all cases as the composition of steel slags varies, 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 conventional LCA and D-LCA as assessment tools has provided valuable additional insights into the environmental impact assessments of mineral carbonation of steel slags in agriculture as a CCUS technology.

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