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RILEM TC REPORT

Life cycle assessment of carbonated recycled concrete aggregates: a critical review and recommendations by RILEM TC 309-MCP

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Abstract This paper by Working Group 1 of RILEM TC 309-MCP presents a critical review of life cycle assessment (LCA) studies on carbonated recycled concrete aggregates (CRCA). Carbonated products can offer significant environmental benefits, particularly by permanently storing CO_2. However, these environmental benefits must be assessed through a comprehensive LCA. A critical analysis of 16 peer-reviewed LCA studies on CRCA reveals several methodological inconsistencies: varied assumptions regarding system boundaries and handling multifunctionality; different end-of-waste criteria and attribution of environmental burdens and benefits among co-products; limited disclosure of key information, including, e.g., technical characteristics of CRCA products, CO_2 uptake and CO_2 sources; and unclear interpretation of negative impact results, without proper distinction between avoided emissions and carbon removals. Overall, the Global Warming Potential (GWP) results for unbound CRCA vary between −48 and 14 kg CO_2e/t CRCA within the analysed studies. These findings underscore the need for harmonised LCA methodologies and transparent reporting to enhance the reliability of LCA studies. A set of methodological recommendations is proposed to enhance LCA consistency, aligned with general LCA guidance and best practices, while being tailored to the specific context of carbonated products. The recommendations cover system boundary definition, multifunctionality handling, modelling of CO_2 flows, reporting of life cycle inventory information, and interpretation of LCA results. This work aims to support both researchers and practitioners in conducting more accurate and comparable LCAs on CRCA and other mineral carbonation products, ultimately

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contributing to the wider adoption of enforced carbonation within the construction sector.

Keywords Carbonation · Recycled concrete aggregate · Life cycle assessment · Carbon capture and storage

Abbreviations

CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation, and storage
CDW	Construction and demolition waste
CRCA	Carbonated recycled concrete aggregate
DCF	Dynamic characterisation factor
EPD	Environmental product declaration
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NA	Natural aggregate
PCR	Product category rule
RCA	Recycled concrete aggregate

1 Introduction

Recycled concrete aggregates (RCA) offer a promising route to reduce the consumption of virgin raw materials and the disposal of construction waste, thereby promoting a circular economy in the built environment [1–3]. Therefore, the use of RCA has been broadly incentivised through different regulations around the world [4–8]. Enforced carbonation has been widely studied as a method to enhance the mechanical performance of recycled concrete aggregates (RCA) by reducing their porosity through the formation of carbonates [9]. More recently, interest in the carbonation of RCA has grown due to the possibility of carbon sequestration as mineral carbonates, thereby providing permanent carbon storage in the product, as even at the product's end-of-life, the stored carbon is not released back to the atmosphere [10–12]. Therefore, carbonated RCA (CRCA) works as a form of Carbon Capture, Utilisation, and Storage (CCUS) and can help mitigate climate change [13, 14]. If the stored carbon is from biogenic or atmospheric sources, carbonated products (not only CRCA) can even provide permanent carbon removal, which can be certified for carbon credits [15, 16], potentially adding further economic value to such products.

However, the contribution of CRCA (and other carbonated products) to climate change mitigation cannot be assessed only based on how much CO_2 they absorb [9]. The processes of capturing and transporting the CO_2, collecting, sorting, and transporting the waste concrete, and the enforced carbonation itself also have associated material and energy requirements and, therefore, direct and/or indirect greenhouse gas (GHG) emissions (and other environmental impacts) that must be considered [12, 17]. Moreover, in some cases, using CRCA instead of natural aggregates may influence the environmental performance of the final product. For example, if a higher cement content is required to maintain an equivalent mechanical performance as that of concrete made with natural aggregates, this could impact the overall environmental footprint [9]. Also, the environmental benefit of CRCA depends on the reference scenario considered, including which product it can substitute, and which impacts can be avoided through carbonation [12]. Therefore, a Life Cycle Assessment (LCA) becomes necessary to effectively evaluate the environmental performance of CRCA and other carbonated products [18, 19].

Multiple LCA studies have been conducted on carbonated construction products [12], especially on CRCA, which is, to date, the most widely adopted carbonated material, including at the industrial scale. However, a harmonised methodological approach is lacking; while some differences may be justified by differences in the LCA goal and scope, others refer to inconsistencies that can potentially limit comparability of LCA studies on CRCA and hinder their use for decision-making [20]. Performing LCA on carbonated products is particularly challenging due to their inherent multifunctionality: besides fulfilling their primary function (e.g., acting as an aggregate in the case of CRCA), they also provide permanent carbon storage—which therefore extends beyond the service life of the carbonated products—and a waste management service. Addressing multifunctionality in LCA requires choices about how to attribute environmental burdens, which are inherently complex and context-dependent [21]. The lack of harmonised end-of-waste criteria to set the boundary between what is considered as construction and demolition waste (CDW) and what is a secondary material (in this case, RCA)—for instance, due to different substances and threshold levels to be verified in leaching tests—poses an additional challenge for such LCA studies [22–28].

This work aims to critically review existing LCA studies on CRCA, analysing how methodological choices were implemented and how these choices influence the LCA results and conclusions of each study. The paper is structured as follows: Sect. 2 presents the methodological LCA aspects analysed, and the LCA guidelines (including guidelines specific to the CCUS context) that were used as a basis; Sect. 3 presents the results of the literature review analysis, providing an overview of the environmental performance of CRCA and identifying key areas of methodological divergence across studies; Sect. 4 presents recommendations to support the development of more consistent and robust LCA studies for carbonated construction products; and Sect. 5 presents the conclusions of this work.

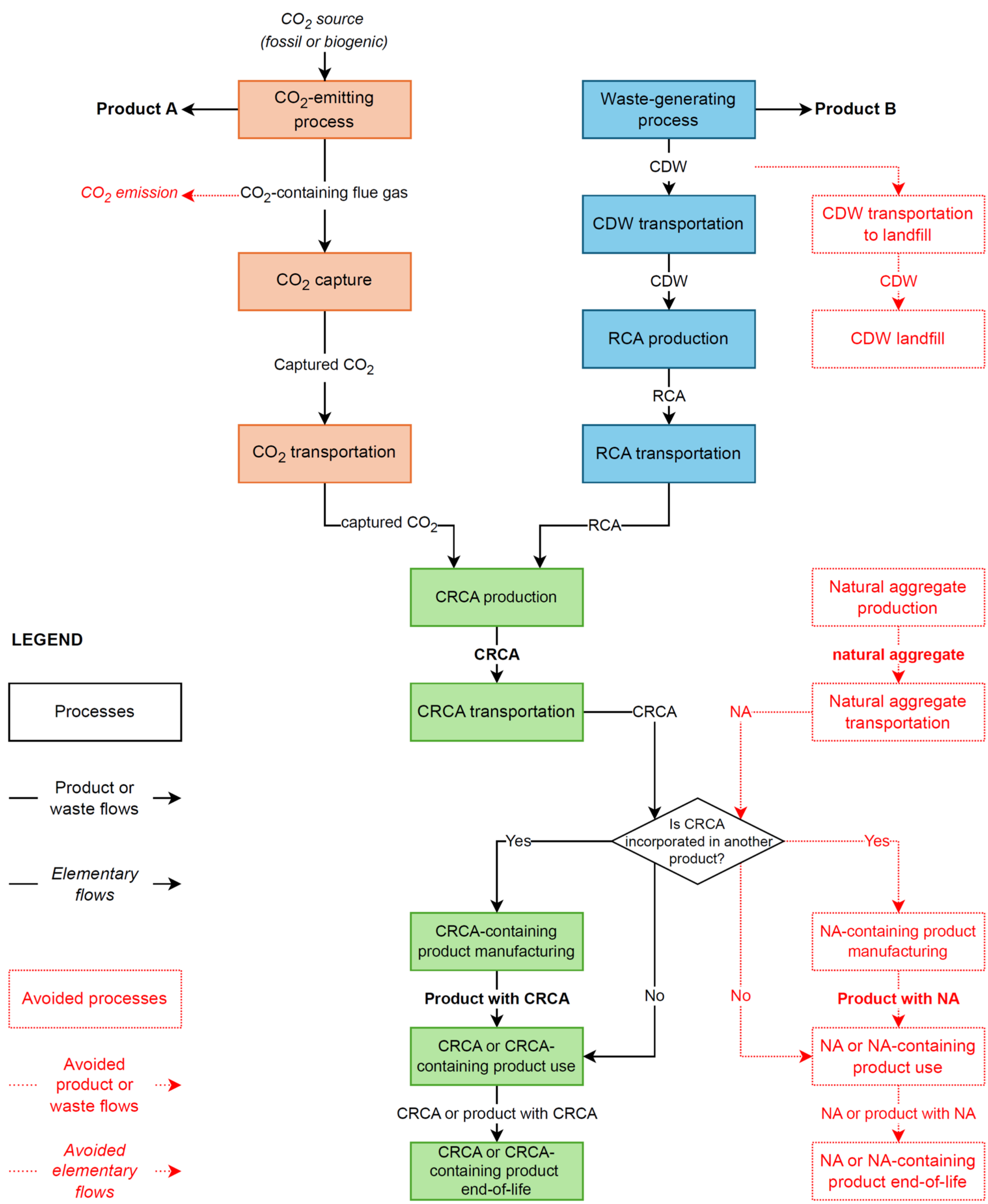
2 Method

The analysis presented in this study is based on a literature review of papers on LCA of CRCA published in scientific journals. Methodological aspects were evaluated in light of the general LCA standards ISO 14040 [29] and ISO 14044 [30]; construction product-specific LCA standards and Product Category Rules (PCR), including ISO 21930 [31], EN 15804 [32], EN 16757 [33], and CEN/TR 17310 [34]; general LCA guidelines [21], LCA guidelines specific to CCUS [19, 35–37]; regulations, and carbon credit certification rules [15, 16]. Based on the outcomes of this analysis, we derive recommendations for conducting LCA studies on CRCAs, which may also be extended to other carbonated construction products.

For each study, we compiled the LCA results and, whenever available, the underlying life cycle inventory (LCI) data. We systematically analysed the following LCA methodological aspects:

- LCA standards and frameworks referred to by each study.
- Goal and scope:
  - o The goal of the LCA study and the type of product analysed.
  - o The declared or functional unit adopted, including, where applicable, the parameters used to characterise the technical performance of CRCA or CRCA-containing product (concrete or mortar).
  - o The life cycle stages and processes included in the system boundary**,** based on the generic framework presented in Fig. 1, which represents a generic system boundary applicable both to unbound CRCA and to products containing CRCA (e.g., concrete). This generic framework does not apply any end-of-waste criteria a priori; depending on those criteria, some processes would be excluded from the system boundary.
  - o The approach adopted to address the inherent multifunctionality of the product system—namely, the simultaneous production of a construction product, provision of permanent CO_2 storage, and treatment of CDW—considering options such as allocation (partitioning), system expansion, and substitution by system expansion.
- Life cycle inventory (LCI):
  - o The sources of LCI data for foreground and background processes.
  - o The method employed to measure or estimate the CO_2 uptake (e.g., thermogravimetric analysis, CO_2 volume measurements, or process mass balance).
  - o The CO_2 source (atmospheric/biogenic, fossil/geogenic, or unknown/not informed).
  - o Any additional relevant metadata, such as specific details about the enforced carbonation.
- The selected life cycle impact assessment (LCIA) categories and characterisation methods.
- The interpretation of the LCA results and corresponding conclusions.

The literature review considered journal papers indexed in the Scopus database. The search string used was “TITLE-ABS-KEY((carbonation OR carbonated) AND recycled AND aggregate AND ("life cycle assessment" OR "LCA" OR "carbon footprint" OR GWP))”, leading to an initial set of 56 papers



published in the last 10 years (2015–2025). After a first screening of the abstracts, 16 papers were selected for detailed analysis, as they allowed us to address all above-listed methodological aspects, thereby providing sufficient information to interpret their LCA results. Figure 2 shows that most of the

◂**Fig. 1** Schematic representation of possible processes in the system boundary of an LCA of CRCA carbonated with captured CO_2, considering a system with a CO_2 source (production process of generic product "A"), a CDW source for the RCA (production process of generic product "B"), and the production of CRCA (unbound) and eventually a CRCA-containing product (for instance, concrete), which substitutes natural aggregate (NA) or an NA-containing product whose production is avoided. By storing CO_2 and recycling CDW, CO_2 emissions and CDW landfilling are avoided, respectively. For simplicity reasons, we do not represent specific product and elementary flows in the different processes; for example, CO_2 uptake due to natural carbonation of stockpiled CDW or CRCA if it is not fully carbonated during the enforced carbonation process

reviewed papers have been published since 2022 and are predominantly from China and Western Europe. While this distribution reflects the current state of the literature, it introduces a geographical bias and should not be taken as an indicator of global research interest or the market adoption of CRCA in other regions. Although including additional studies could increase the number of reported LCA results, their limited methodological transparency would not contribute to the core objective of this review, which is to assess the influence of LCA methodological choices on the results and conclusions of the analysed studies.

The list of all studies reviewed, with all the compiled LCA information, is available in the Supplementary Information (see Data Availability).

3 Analysis of published LCA studies

3.1 LCA standards and frameworks

Half of the analysed studies explicitly refer to LCA standards, while the other half does not mention using specific standards. Four studies refer to the international LCA standards ISO 14040 and ISO 14044 [17, 38–40], whereas one refers only to ISO without specifying the standards [41]. The other three studies refer to LCA standards specific to construction products, including the Chinese standard for calculating the carbon emissions of buildings GB/T 51366 [42], the European PCR for construction products EN 15804 [43], and the European PCR for cement and concrete products EN 16757 [44]. Among the studies not relying on LCA standards, some refer to other LCA frameworks, such as Müller et al. [45] guidelines for LCA of CCU technologies and Tanzer and Ramírez [36] criteria for accounting for negative CO_2 emissions [17], or a Chinese building environmental performance assessment system (short BEPAS) [46]. Moreover, some studies cite prior LCA studies on similar products as their background [38, 47, 48].

3.2 Goal definition and type of product analysed

Most studies (75%) aim at evaluating the environmental benefits of CRCA over alternatives, while only 25% aim only at declaring the LCA results of CRCA without performing any comparison (See Fig. 3). The most frequent comparison is with other aggregate types, either natural aggregates [47, 48], or uncarbonated RCA [49], or both [39, 41–43, 50]. Two studies compare carbonation with other methods for improving RCA characteristics (for instance, thermal treatment) [38, 46]. The other two studies compare CRCA with other carbon capture and storage (CCS) technologies, including other carbonated products [12] and underground CCS [12, 51], thereby focusing on the permanent CO_2 storage function rather than on the product itself.

Regarding the type of product analysed, half of the studies consider the production of CRCA [12, 40, 46, 48–52], while the other half consider the production of concrete or mortar containing CRCA [17, 38, 39, 41–44, 47]; some of the latter allow the isolation of CRCA results. Ten studies assess specific products and processes, including theoretical formulations [40, 52], some developments at the laboratory scale [39, 42, 47, 49, 50], and products already at the pilot [44] or industrial scale [17, 51], whereas the remaining six studies draw conclusions on generic CRCA and/or CRCA-containing products [12, 38, 41, 43, 46, 48]. All analysed studies conduct attributional LCA.

3.3 Functional or declared unit and reference flow

LCA studies focusing on CRCA usually adopt a mass unit (kg or t), whereas studies of concrete or mortar with CRCA adopt a volume unit (m^3) as reference flow. Assessing the environmental impact per ton or m^3 may seem sufficient for applications like unbound material or even non-structural concrete; however, the mechanical and durability performances may be affected by factors such as the porosity or contaminant content in CRCA compared to virgin aggregates,

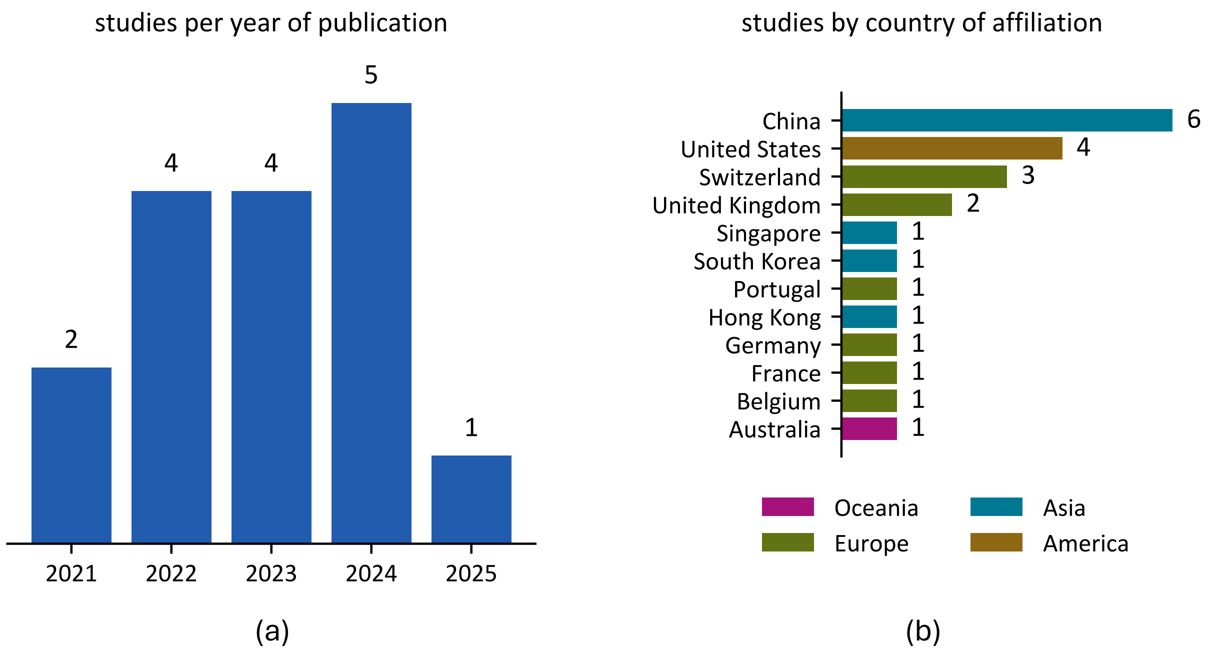
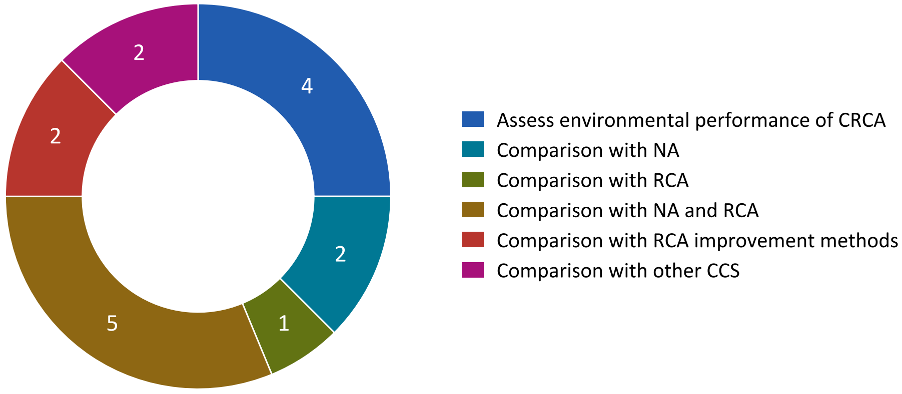


Fig. 2 Number of analysed papers by year of publication (**a**) and country of affiliation of the authors (b). The sum of the numbers disclosed in (**b**) exceeds 16 because five papers have authors from different countries

Fig. 3 Number of LCA studies by goal



making it necessary to also consider technical characteristics as part of the functional unit definition.

Among the technical characteristics used to describe the functional or declared unit, the most frequently used is the particle size grading, followed by water absorption, density, and crushing value. Six studies focus on coarse aggregates [17, 38, 41, 49–51], three studies only consider fine aggregates [39, 47, 52], two studies consider both types [42, 44], and five studies do not inform their particle sizes [12, 40, 43, 46, 48]. For concretes and mortars, all studies report the percentage of CRCA replacing virgin aggregate (ranging from 10 to 100%). Most of these studies also report the compressive strength (ranging from 25 to 125 MPa), which is an important characteristic, as incorporating CRCA can reduce concrete strength compared to mixes made with only virgin aggregates. Five studies, however, do not provide any technical characteristics of their products [12, 40, 43, 46, 48].

3.4 System boundary and multifunctionality

Table 1 presents the system boundary adopted by each LCA study (note that some studies present results for multiple system boundaries), considering the life cycle stages and processes outlined in Fig. 1. Included stages are those explicitly identified by the studies in their system boundary descriptions, either as a flowchart or in text. "Partially included" stages refer to cases in which not all relevant flows were included in the LCI (for instance, considering only the CO_2 uptake during carbonation but not the energy consumption of the carbonation equipment), whereas "implicitly included" stages refer mostly to avoided impacts that were modelled as such (evident from negative GWP values, for instance), but the study did not mention applying substitution/avoided impacts to handle multifunctionality.

An initial comparison reveals that no study shares the same system boundary. The varied objectives of the studies partially explain this difference – for example, some comparative LCA studies exclude life cycle stages that are common between the compared alternatives. However, even studies with similar goals have different boundaries (for instance, Xiao et al. [42] and Brazão Farinha et al. [43], both comparing concrete or mortar with CRCA with those made with NA and RCA; or Tiefenthaler et al. [17] and Ang et al. [40], both declaring the environmental performance of CRCA), which indicates a certain lack of methodological harmonisation. Nevertheless, all studies agree upon considering the CO_2-containing flue gas as a waste stream with no allocated environmental burden from the CO_2-emitting process (only accounting for burdens from the CO_2 capture process onwards), and only one study [47] considers CDW with some environmental burden.

Most studies consider the CO_2 capture and/or transportation steps, although it could be debated whether this burden should instead be attributed to the process emitting the CO_2. In some of these studies, the CO_2 capture step also involves a CO_2 compression sub-step to enable CO_2 transportation between the CO_2 source and the carbonation facility. Seven studies consider the impact of transporting CDW to the recycling plant, while several others argue that this impact should be attributed to the waste generator. This demonstrates an internal inconsistency in the application of end-of-waste criteria between the two main waste streams.

Processing CDW into RCA is considered by almost all studies, with only one unjustified exception [40]. Depending on the end-of-waste criteria applied, the impact from the concrete recycling processes into RCA can be attributed to the life cycle of the waste-generating product (module "C3" according to EN 15804), meaning that the process of crushing, sieving and separating recovered end-of-life concrete would be outside the RCA production scope. Most studies consider the enforced carbonation process itself, while four studies consider only the CO_2 uptake [41–43, 50], thereby disregarding any other impacts associated with enforced carbonation. Half of the studies go beyond CRCA production and also consider the production of concrete or mortar with CRCA. No study considered the use and end-of-life stages, although only three studies justified this choice [17, 38, 42]. Also, no study considered subsequent life cycles of the CRCA or CRCA-containing products, that is, their recycling after the end-of-life (module "D" according to EN 15804).

Assumptions regarding how to handle multifunctionality are less clear. Eleven studies consider avoided impacts by applying substitution through system expansion; however, only five of these are explicit about this methodological approach [12, 41, 42, 48, 50]. All studies that account for avoided processes consider avoided CO_2 emissions (from the CO_2-emitting process), five consider the substitution of natural or recycled aggregates by CRCA (avoiding the impacts of producing the substituted aggregates based on current technology), and three consider avoided CDW landfilling. Only one study considered all three avoided processes simultaneously [12] (the avoided waste landfilling was however attributed to the RCA production step). In all cases of avoided impacts, the GWP values are modelled as negative impacts, subtracted from positive GWP results, and attributed to the CRCA or CRCA-containing product. Most of the other five studies adopted allocation (also known as partitioning). Only one study adopted system expansion, declaring the joint impact of CO_2 capture (from biogas upgrading) and storage through CRCA production, which was later compared to CCS with underground storage (but without including natural aggregate production in the reference scenario) [51]. Another inconsistency noted is that three studies

Table 1 System boundary adopted by each LCA study and avoided processes considered. Some studies present results for more than one system boundary

References	CO_2 supply			RCA supply				CRCA	Concrete or mortar with CRCA				Use	EOL	Avoided processes		
	CO_2-emitting process	CO_2 capture	CO_2 transportation	Waste-generating process	Waste transportation	RCA production	RCA transportation	CRCA production (carbonation)	Raw materials production	CRCA transportation	CRCA concrete/ mortar production	CRCA concrete/ mortar transportation	CRCA or concrete/ mortar use	CRCA or concrete/ mortar end-of-life	CO_2 emission (CO_2-emitting process)	Waste landfill	Production of substituted product
Driver et al. [12]	o	x	–	o	x	x	–	x	o	o	o	o	o	o	x	x	x
Tiefenthaler et al. [17]	o	–	x	o	–	x	x	x	o	o	o	o	o	o	o	o	o
	o	–	x	o	–	x	x	x	x	x	x	–	–	–			
Rosa et al. [51]	o	x	x	o	–	–	–	x	o	o	o	o	o	o	o	o	o
Izoret et al. [44]	o	x	–	o	–	/	x	x	–	x	o	o	o	o	o	o	o
	o	x	–	o	–	/	x	x	–	x	/	o	o	o	(x)	o	x
Pu et al. [38]	o	x	–	o	x	x	x	x	x	x	x	–	–	–	(x)	o	o
Villagrán-Zaccardi et al. [47]	o	o	o	/	x	x	–	x	x	x	x	o	o	o	(x)	o	o
Yuan et al. [41]	o	x	o	o	x	x		/	o	o	o	o	o	o	x	x	o
	o	x	o	o	x	x	o	/	x	x	x	o	o	o			
Xiao et al. [42]	o	x	o	o	x	x	x	/	x	–	x	o	–	–	x	x	o
Zhang et al. [48]	o	x	x	o	x	x	–	x	o	o	o	o	o	o	x	o	x
															x	o	o
Huang et al. [39]	o	o	o	o	o	x	x	x	x	o	o	o	o	o	(x)	o	o
Feng et al. [46]	o	o	o	o	–	–	–	x	o	o	o	o	o	o	o	o	o
Hosseini Zadeh et al. [50]	o	o	o	o	o	x	o	/	o	o	o	o	o	o	x	o	x
Chen and Yang [52]	o	x	x	o	o	x	–	x	o	o	o	o	o	o	o	o	o
Jeon et al. [49]	o	o	o	o	o	x	o	x	o	o	o	o	o	o	o	o	o
Ang et al. [40]	o	x	–	o	o	o	o	x	o	o	o	o	o	o	(x)	o	o
Brazão Farinha et al. [43]	o	x	–	o	x	x	x	/	x	x	x	o	o	o	(x)	o	(x)

Legend

x Included / Partially included (x) Implicitly included – Not included and justified o Not included and not justified consider the benefit of avoided CO_2 emissions, but not the burdens of carbon capture [39, 47, 50].

3.5 Life cycle inventory

Ten of the sixteen analysed studies use primary data for the foreground enforced carbonation, whereas the remaining six rely on literature data (see Fig. 4). Most studies using primary data are based on laboratory experiments [39, 42, 47, 49, 50]. Therefore, their results may not accurately represent real-world situations, as such experiments can, at best, estimate CO_2 uptake but not other process-related parameters, such as energy consumption, performance variability, and contamination levels. Furthermore, laboratory experiments may overestimate CO_2 uptake due to the use of RCA made from recent concretes (without prior natural carbonation as usual for RCA, which would otherwise limit the CO_2 uptake by the enforced carbonation of CRCA). One study is based on data from pilot plants [44], and two are based on industry data [17, 51], both referring to the same industrial operation.

Given the importance of the CO_2 uptake for the LCA, Fig. 5 shows the values retrieved from the analysed references according to the CO_2 uptake determination method. The reported values range from 5.0 to 49.0 kg CO_2/t CRCA. The most common data source is literature, followed by measurements (thermogravimetric analysis (TGA) and loss on ignition (LOI) being mentioned). One study relied on simulations [52], while another considered the theoretical maximum uptake potential [12]. Only one study performed a mass balance of CO_2 input and output in the enforced carbonation [17]. For more information about CO_2 uptake measurement methods, please refer to Matschei et al. [53]. Three studies do not report their CO_2 uptake values [39, 46, 49], representing a relevant data gap that undermines their reproducibility. Although some studies analyse generic products (as discussed in 3.2), most of them rely on deterministic estimates of CO_2 uptake by CRCA [12, 38, 41, 48], thereby disregarding the inherent variability of this parameter as demonstrated in Fig. 5; one exception is Brazão Farinha et al. [43], who consider different types of recycled aggregates with different CO_2 uptake values.

Further to the critical analysis of the claimed potential CO_2 uptake of the CRCA products studied, it is important to highlight that none of the reviewed

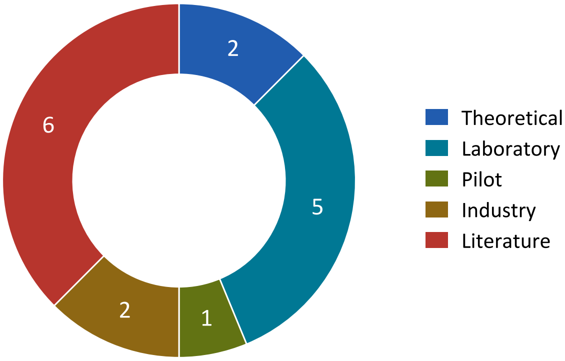


Fig. 4 Number of LCA studies by type of foreground data

articles reported the initial carbon content in the RCA subject to carbonation. It is known that natural carbonation would result in an uptake of approximately 2–20 kg CO_2/t of the previous concrete throughout its service life, depending on the exposure conditions, binder type and concrete properties [54]. The residual paste attached to the RCA after recycling and before the enforced carbonation process would then be expected to carry a fraction of this CO_2, which should hence be deducted from the carbon mitigation potential of the CRCA products under study. As no study considered the use, end-of-life, and future use stages of CRCA or CRCA-containing products, it was not possible to account for the eventual CO_2 uptake in these future stages (for instance, if the CRCA is not yet fully carbonated).

Another important LCI information is the CO_2 source, as it directly influences the Global Warming Potential (GWP) results. Figure 6a shows that only nine of the sixteen studies inform the CO_2 source, most of them considering fossil CO_2, two studies considered biogenic CO_2 (from biogas upgrading) [17, 51], and one atmospheric CO_2 from direct air capture [52]. The CO_2 concentration used in the process varies, as shown in Fig. 6b. Most studies consider pure CO_2, meaning it had to be captured (i.e., separated from the flue gas) and stored previously. In five studies, the CO_2-containing flue gas is directly used [38, 41–44]; therefore, carbonation works simultaneously as carbon capture and storage in these cases.

Seven of the analysed studies disclose sufficient inventory information to allow for reproducing them [12, 17, 38, 41, 47, 49, 52]. Six other studies disclose some additional data, but they are insufficient to

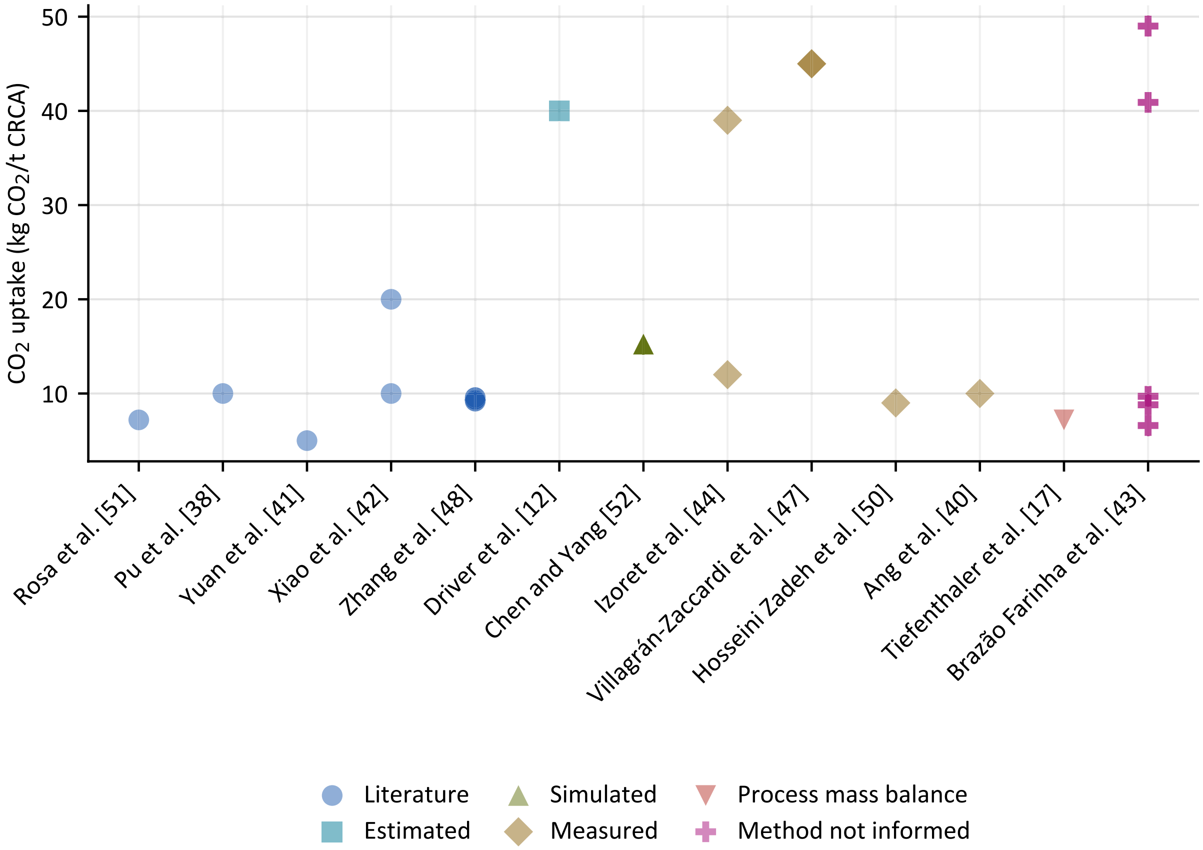


Fig. 5 CO_2 uptake by estimation method and LCA study (studies not shown in the chart did not report CO_2 uptake values)

reproduce the LCA calculations [42–44, 46, 48, 51]. Three studies do not disclose any additional information [39, 40, 50]. The most common source of background LCA data is the Ecoinvent database, which was mentioned in nine studies; GaBi, ELCD, and the Chinese CLCD were also used.

None of the analysed studies has conducted a comprehensive uncertainty assessment on the life cycle inventory input and output flows. However, some studies conducted scenario or sensitivity analyses, with the transportation distance of the recycled aggregates being the most investigated parameter [17, 38, 42, 47, 48], followed by the carbon intensity of electricity [17, 48], the CO_2 uptake [17, 48], and energy use [40, 52]. These parameters were varied either within ranges considered reasonable [17, 42, 47, 52] or by an arbitrary relative variation (e.g., ± 10%) [48].

3.6 Life cycle impact assessment

Figure 7 shows the GWP results for 1 t of CRCA, either as reported or calculated from the LCA results disclosed by each study considering their corresponding system boundaries and multifunctionality handling procedures. The following studies did not allow for the extraction of GWP results for 1 t of CRCA: Rosa et al. [51] only report results for the expanded system; Pu et al. [38] present LCA results for concrete with CRCA without sufficient data to separate the CRCA from it; and Feng et al. [46] did not assess this impact category. The GWP results vary between -48 and 14 kg CO_2e/t CRCA. Jeon et al. ([49] presented GWP results of 196 and 335 kg CO_2e/t CRCA,

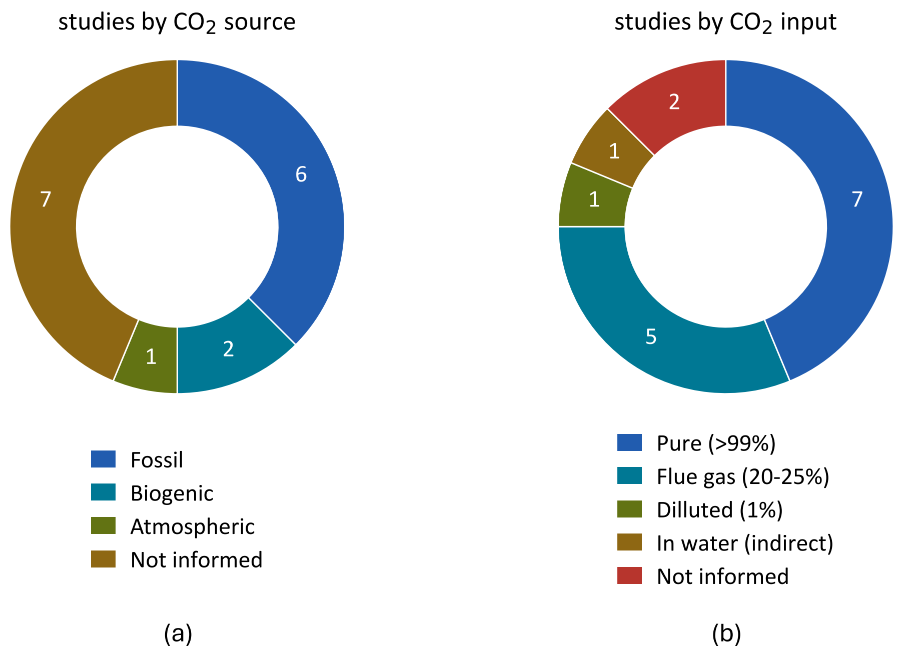


Fig. 6 Number of LCA studies by CO_2 source (**a**) and concentration of CO_2 used in the enforced carbonation (**b**)

which were omitted from the chart because they were considered outliers.[1]

The majority of the GWP results (74%) are negative values. However, in only two studies, these negative values indicate product systems that remove more CO_2 from the atmosphere than they emit [36], because their processes utilise biogenic [17] or atmospheric CO_2 [52]. In the latter case, the high energy intensity of the direct air capture process results in a positive overall GWP in some scenarios. In all other cases, the negative GWP values should be interpreted as representing an impact reduction relative to a reference scenario with higher overall CO_2 emissions [55], which is why the types of avoided impacts considered by each study are highlighted in the legend of Fig. 7.

Figure 8 summarises the contribution analysis of the GWP for 1 t of CRCA based on available or calculated process-level data from nine of the sixteen studies. Most studies show moderate positive contributions, below 10 kg CO_2e/t CRCA, mainly associated with waste recycling, CRCA production and RCA transportation. Driver et al [12] is an exception, with higher contributions from RCA transportation and enforced carbonation processes (mainly due to 39 kg CO_2/t CRCA injected into the carbonation reactor but not absorbed by the RCA, being reemitted into the atmosphere). Negative GWP results are explained mainly by avoided or removed CO_2 emissions and generally limited to -20 kgCO_2e/t CRCA, except for two studies with higher CO_2 uptake considerations (40 kg CO_2e/t CRCA by Driver et al. [12], 45 kg CO_2e/t CRCA by Villagrán-Zaccardi et al. [47]). In the case of Driver et al. [12], they report 79 kg CO_2e/t CRCA as avoided emissions, although net avoided emissions are 40 kg CO_2e/t CRCA (the other 39 kg CO_2e are included in the positive impacts of CRCA production according to their reporting approach). It is important to remind that the CO_2 uptake of RCA is composition-dependent. A further transition towards reduced clinker content in future concrete will also decrease the impact of CO_2 removal and avoided CO_2 emissions achieved via enforced carbonation of future RCA, compared to the values in Fig. 8. Avoided natural aggregate extraction due to its substitution by the CRCA, and avoided CDW landfill processes show a limited contribution to negative GWP results.

[1] The authors identify "*the amount of fuel [diesel] used in the process*" as "*the main factor in carbon dioxide emissions*", but they do not benchmark their GWP results against the existing literature. Given the described CRCA production process (a series of screens and crushers followed by CO_2 treatment), we consider such a high GWP unlikely. This discrepancy may indicate an error in the underlying inventory; however, this hypothesis cannot be tested, as the LCI is not reported in sufficient detail to be entirely reproduced.

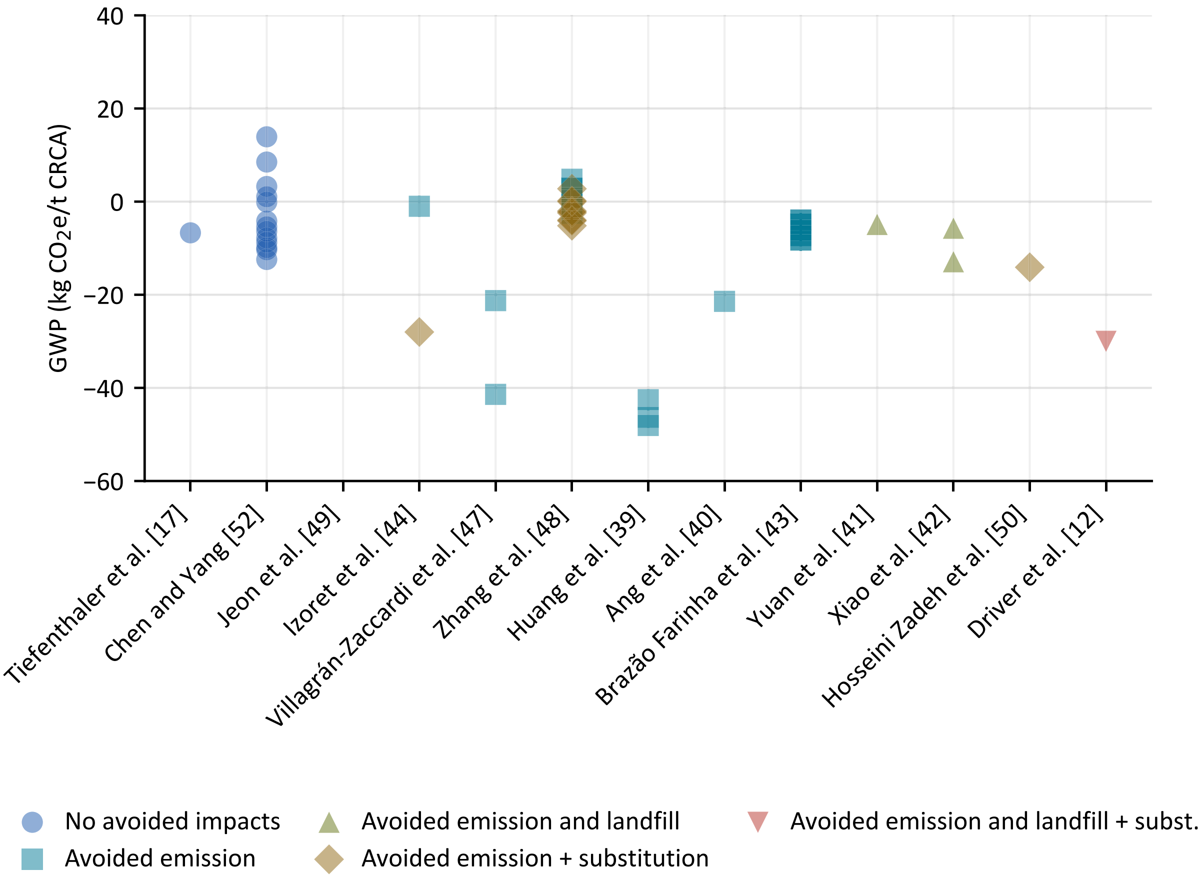


Fig. 7 GWP results for 1 tonne of CRCA, classified according to which avoided emissions were considered by each study (studies not shown in the chart did not report GWP results; Jeon et al. [49] was considered an outlier)

None of the works considered performed dynamic LCA. Dynamic LCA considers the timing of GHG emission or removal by using dynamic characterisation factors (DCFs) [56]. The DCFs are based on atmospheric models that consider the radiative forcing, as well as the decay of the atmospheric load of any GHG, starting from its emission to or removal from the atmosphere [56]. Static LCA, on the other hand, considers the warming induced by all emissions and removals during the same time horizon, regardless of when these GHG flows happen (which is mathematically equivalent to considering that all emissions and removals happen at time zero).

Figure 9 shows an illustrative example of dynamic LCA results for 1 kg of CO_2 being emitted at time zero and at 50 years. In Fig. 9a, we illustrate the instant radiative forcing caused by each emission, that is, the energy gained by the atmosphere following an emission pulse, showing that there is an energy peak immediately after the emission, later attenuated by carbon absorption mechanisms of the Earth [57]. Figure 9b shows the cumulative radiative forcing, also known as Absolute Global Warming Potential, which is the integer of the instant radiative forcing curves [57]. Figure 9c shows the relative impact that corresponds to the GWP as usually known in LCA, which is calculated as the ratio between the cumulative radiative forcing of GHGs over a certain time horizon (usually 100 years) and the cumulative radiative forcing of 1 kg of CO_2 emitted at time zero (and is therefore expressed in kg CO_2e). In static LCA, both would have a GWP-100 of 1 kg CO_2e, while in dynamic LCA, the emission that happens later has a GWP-100 of 0.6 kg CO_2e (on the long run, after more than 500 years, GWP results tend to converge).

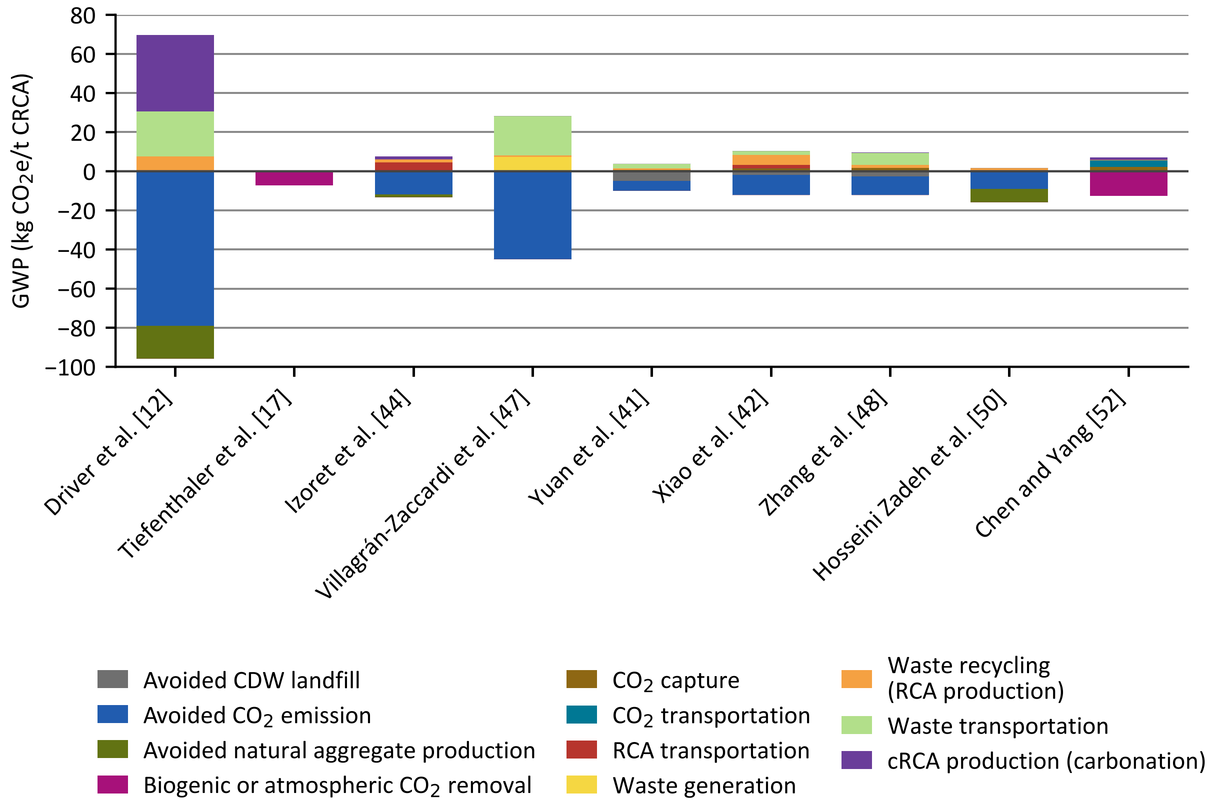


Fig. 8 Process contribution analysis of GWP emissions for 1 tonne CRCA based on nine studies

If the objective is only to estimate the GWP of enforced carbonation products, dynamic LCA is not essential, since emissions and removals mostly happen at the same time. However, if the LCA study involves comparing enforced carbonation products with products that would naturally carbonate—including RCA—dynamic LCA would be recommended, as the static LCA disregards the significantly slower kinetics of the natural recarbonation process [58, 59]. To perform a dynamic life cycle assessment, the LCI should include the year of emissions and removals, and then, the effect of each emission or removal is accounted for by multiplying it by the corresponding DCFs [56]. Tools such as dynCO_2 [60] and the Brightway package Timex [61] can support dynamic LCA implementation.

Only four studies [17, 38, 40, 46] considered other midpoint impact categories than GWP, and no study conducted the assessment at the endpoint level. Among these studies, Ang et al. [40] used the CML2001 impact assessment method to evaluate a CO_2 capture and storage technology through aqueous ammonia absorption followed by RCA carbonation. The production of sulphuric acid consumed in the process and its upstream processes led to significant contributions in acidification, freshwater ecotoxicity, human toxicity, terrestrial ecotoxicity, and photochemical ozone creation. The other three comparative LCA studies by Tiefenthaler et al. [17], Pu et al. [38], and Feng et al. [46] respectively adopted Environmental Footprint 3.0, CML2001, and BEPAS (a method that expresses the environmental impact in a single economic value) as LCIA methods. In all cases, CRCA outperforms the alternatives regardless of the impact category.

3.7 Interpretation

Since 75% of the LCA studies had a comparative objective, the most common approach was to compare the GWP results with relevant references. Eleven studies conducted some form of contribution analysis

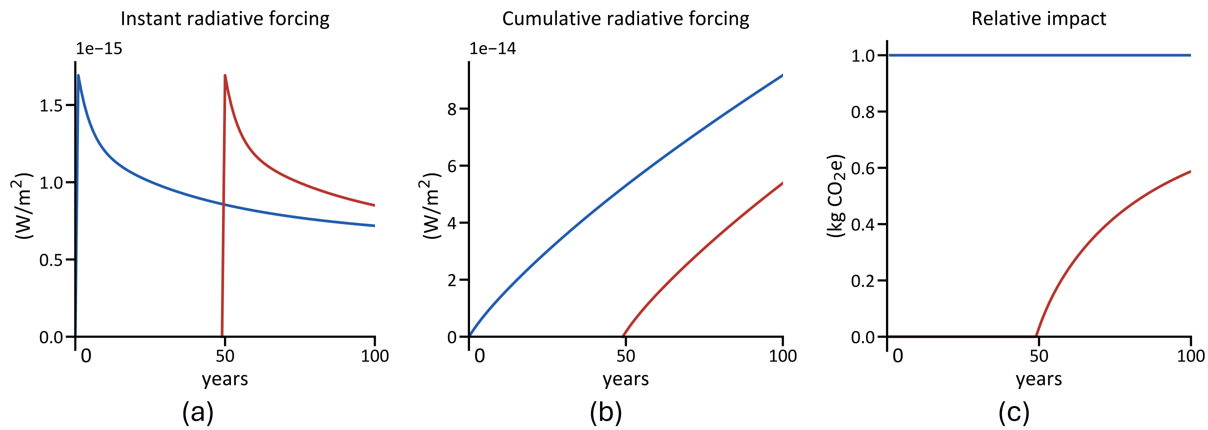


Fig. 9 Schematic dynamic LCA results of 1 kg of CO_2 being emitted at time zero (blue curve) and at 50 years (red curve): (**a**) instantaneous radiative forcing caused by emission; (**b**) cumulative radiative forcing over 100 years; (**c**) relative impact to 1 kg of CO_2 emitted at time zero over 100 years (GWP-100). In static LCA, both emissions would have a GWP of 1 kg CO_2e

(as discussed in Sect. 3.6; however, only nine of them provided sufficient information to allow for reproducing the analysis in Fig. 8), while seven studies performed sensitivity analysis, with the most frequently investigated parameter being the transportation distance of RCA. Because RCAs have a relatively low carbon footprint, transportation plays an important role in their environmental competitiveness [62–64].

Table 2 presents an overview of the main conclusions from each study regarding the use of CRCA, including whether they are generally in favour of CRCA production and use. Most studies (75%) are favourable to CRCA, primarily because CRCA demonstrates better performance than RCA [17, 39, 41, 42, 47], with additional avoided emissions. Rosa et al. [51] conclude that the amount of CO_2 that could be stored in CRCA (in Switzerland) is much lower than the potential of underground CO_2 storage, yet CRCA could still be a suitable "BECCUS" (bioenergy with carbon capture, utilisation, and storage) solution for some CO_2 sources (the biogenic CO_2 is captured from biogas upgrading facilities). Two other studies [48, 52] conclude that the environmental benefits of CRCA depend on transportation distances and energy mix. The only study unfavourable to CRCA [12] does not justify its position on environmental grounds, but rather on the poor economic competitiveness of enforced carbonation compared to underground CCS for permanent carbon storage. Indeed, the economic feasibility of CRCA should be better investigated to support decision-making, also considering that it can avoid concrete waste landfilling (where it is allowed) and CO_2-related costs (carbon emission taxes or costs for underground CCS), and eventually generate credits for CO_2 removal [16], which requires integrating LCA and cost analyses.

An additional, but crucial, point regarding the interpretation of LCA results is how negative GWP values are understood and presented by different studies. As discussed previously, only three studies [17, 51, 52] use biogenic or atmospheric CO_2 sources and could thus legitimately achieve truly negative GWP values, indicating net removal of CO_2 from the atmosphere. However, some studies using fossil or unknown CO_2 sources also claim that "*production of carbonated recycled aggregate can be carbon negative*" [12], "*the contribution of fine RCA was even negative when considering the CO_2 uptake*" [47], "*CRCA has the potential to produce negative CO_2 emissions*" [44], "*9 g of CO_2 were consumed to treat 1 kg of RCA […], it can be translated to negative 16.2 million tons of CO_2 every year*" [41]. These statements may give the misleading impression that such product systems act as carbon removal technologies, implying that increasing CRCA production would serve as an endless carbon sink. However, the correct interpretation, aligned with best practices in LCA reporting, is that in these scenarios, negative GWP values represent reductions relative to a reference system with higher CO_2 emissions, and not actual removals of atmospheric CO_2. In other words, unless the CO_2 source is truly biogenic or atmospheric, the

Table 2 General conclusions of the analysed studies regarding the use of CRCA

Study	Conclusion about CRCA	Details
Driver et al. [12]	Unfavourable	CRCA is "carbon-negative" but not cost-competitive with RCA production and underground CCS. CRCA has a GWP 0.03 kg CO_2e/kg lower than conventional RCA
Tiefenthaler et al. [17]	Favourable	CRCA using biogenic CO_2 is an efficient permanent carbon sink
Rosa et al. [51]	Neutral	CRCA has limited CO_2 storage potential compared to underground CCS, but it can be a good solution for short distances between CO_2 sources and CRCA production and use
Izoret et al. [44]	Favourable	Enforced carbonation of recycled sand yields a GWP of-28 kg CO_2e/ton, while for recycled gravel, GWP is –1 kg CO_2e/ton (negative results include the effects of avoided CO_2 emissions and product substitution). CRCA can reduce the GWP of concrete by up to 10%, depending on the substitution rates
Pu et al. [38]	Favourable	CRCA has a lower environmental impact than NA and RCA subject to thermal treatment. In some cases, CRCA alone has negative GWP values (due to avoided CO_2 emissions). Replacing all NA with CRCA reduces the GWP of concrete by 3.9%
Villagrán-Zaccardi et al. [47]	Favourable	Mortars with CRCA have lower GWP than mortars with NA, even if the negative effect of avoided CO_2 emissions is not considered. Compared to untreated RCA, carbonation of RCA reduces mortar GWP by about 4%; compared to NA, by about 9–10%
Yuan et al. [41]	Favourable	CRCA has 4.9% and 1.5% lower GWP than NA and RCA, respectively, mainly due to avoided CO_2 emissions and CDW landfilling
Xiao et al. [42]	Favourable	Concrete with CRCA has a carbon footprint (kg CO_2/m^3) and carbon intensity (kg $CO_2/(m^3.MPa)$) between 6 and 13% lower than concrete with NA. Compared to concrete with RCA, the carbon footprint of concrete with CRCA varies from + 1% to -11%, and carbon intensity from -135 to -23%
Zhang et al. [48]	Neutral	CRCA has the potential to produce "negative CO_2 emissions" compared to NA, but the results highly depend on regional characteristics, mainly transportation distances
Huang et al. [39]	Favourable	Concrete with CRCA has GWP 1.6% to 4.6% lower than concrete with natural aggregates and 0.8% to 2.4% lower than concrete with RCA. It can also be cost-effective
Feng et al. [46]	Favourable	CRCA has up to 95% lower environmental impact than other methods to enhance RCA mechanical performance
Hosseini Zadeh et al. [50]	Favourable	CRCA can lead to a negative "net change of CO_2 emissions" by substituting NA and avoiding CO_2 emissions. Standard RCA already reduces GWP by 75% vs. NA, but carbonation turns RCA into a "net carbon sink" (–0.009 vs. + 0.0017 kg CO_2e/kg). CO_2-treated RCA is over 6 times better than untreated RCA
Chen and Yang [52]	Neutral	CRCA combined with direct air capture is viable for carbon dioxide removal if implemented under favourable engineering conditions and in locations with access to clean electricity
Jeon et al. [49]	Favourable	CRCA has a lower GWP than RCA. Simplified CO_2 treatment reduces GWP by 41% compared to conventional RCA process
Ang et al. [40]	Favourable	Using CRCA to capture and store CO_2 from natural gas combined cycle power plant is a viable solution (mainly due to avoided CO_2 emissions)
Brazão Farinha et al. [43]	Favourable	Incorporating CRCA reduces the GWP of mortars between 4 and 37% compared to mortars with NA and RCA

system avoids emissions but does not constitute a net negative emission technology.

4 Recommendations

The critical review of LCA studies on CRCA reveals significant methodological variability, which limits comparability and reproducibility. While most studies highlight CRCA having lower GWP than natural aggregates or untreated RCA, inconsistencies in system boundaries, CO_2 source definitions, and methods to handle multifunctionality lead to diverging results. Negative GWP values are often reported without distinguishing between CO_2 removal and avoided emissions. Additionally, many studies overlook the initial carbon content of RCA, thereby overestimating the CO_2 sequestration potential of CRCA and, consequently, their environmental benefits. The lack of transparent and standardised LCI reporting further undermines the robustness of LCA studies and limits the potential of using them for decision-making.

Based on the observed shortcomings, we propose structured recommendations to support future LCA studies of CRCA and, more broadly, carbonated construction products. These recommendations are generally aligned with established LCA guidelines and good practices, including specifications tailored to the context of carbonated product manufacturing for CCUS. As such, they do not replace existing LCA guidelines and standards; rather, they complement them. They aim to enhance the comparability and reproducibility of LCA studies on carbonated products, thereby avoiding accusations of greenwashing. While the guidelines presented here are broadly applicable, their adoption should be carefully considered by the LCA practitioner in light of the specific goals and scope of each study.

4.1 LCA standards and frameworks

- The **LCA standards, frameworks and guidelines** used to conduct the LCA study should be **explicitly cited**. In case there are any deviations from their recommendations, those should also be highlighted in the LCA report.

4.2 Goal definition

- The **goal of the LCA study must be declared**, including the target audience and, if applicable, the decisions it aims to support. If the study is intended to facilitate publicly available comparisons, all provisions outlined in LCA standards for comparative LCA studies must be followed, including third-party verification.

4.3 Functional or declared unit

- The recommended reference flow for unbound CRCA is **mass**, with **particle size and specific density** reported as a minimum, as aggregates do not always behave the same (finer aggregates have more specific surface area and can absorb more CO_2; on the other hand, they require additional grinding energy). Additionally, it is desirable to report further technical characteristics relevant to the intended application (such as water absorption, attached paste/mortar content, and crushing index for unbound CRCA).
- The recommended reference flow for concrete or mortar containing CRCA is **volume**, and the **compressive strength and mix design** (including the proportion of CRCA) should be reported as a minimum.
- In comparative LCAs, the functional unit should reflect the **functional equivalence** between the compared products. For concrete or mortar containing CRCA, a practical alternative to optimising the mix for identical mechanical and durability performance is to scale the impacts according to the varying strength and durability (for instance, kg $CO_2e/(m^3 \cdot MPa \cdot year)$), dividing the GWP (kg CO_2e) by the concrete volume (m^3), the compressive strength (MPa), and the service life (year) estimated based on exposure conditions [65].
- The functionally equivalent product considered in comparative LCA should be consistent with the goal and scope of the study and allow for a fair comparison. For example, if a study compares a concrete with CRCA with concrete with natural aggregates, both mix designs should be formulated with the same basis; in other words, one

should not compare a highly-optimised mix design with low-carbon cement for the CRCA-containing product, while using a carbon-intensive cement and no optimisation for the equivalent product.

4.4 System boundary

- The system boundary should be **clearly defined**, preferably presented as a flowchart. The life cycle stage designations shown in Fig. 1 and Table 1 can serve as a reference.
- The system boundary must be **consistent with the goal and scope** of the study:
    - o If the study's goal is to **declare the environmental performance** of CRCA or concrete/mortar containing CRCA (e.g., for an Environmental Product Declaration—EPD), the **minimum system boundary is cradle-to-gate** [31, 35] covering raw materials' input up to the end of CRCA or CRCA-containing product manufacturing, including carbonation (modules "A1" to "A3"). If the CRCA or the product containing CRCA can undergo natural recarbonation over the use stage, module "B1" (use) should also be included in the minimum system boundary, since it is the module where the CO_2 uptake from natural recarbonation should be accounted for. For EPDs required to comply with EN 15804, the minimum scope should also include the waste disposal stages (module "C") [32].
    - o For **comparative LCAs**, the system boundary should include the life cycle stages where natural recarbonation could occur. For example, if CRCA is compared to RCA, the LCA should consider the natural recarbonation of RCA (and of the CRCA, in case it is not yet fully carbonated) while it is stockpiled, used, and disposed of over the time horizon of the LCA study. Considering the varying rates of carbonation in such scenarios, a dynamic LCA approach should be applied to ensure accuracy (see recommendations for "Life Cycle Impact Assessment").
    - o If benefits and burdens beyond the life cycle of the CRCA or CRCA-containing product are included in the system boundary (module "D" according to EN 15804), it is crucial that those are attributed to the life cycle stages where they occur to avoid double-counting. For instance, if a CRCA-containing concrete is recycled at the end of its service life as RCA, it may undergo a new carbonation step (not of the CRCA incorporated into the concrete, but of the part of the cement that is uncarbonated), avoiding further CO_2 emissions, waste landfilling, and the extraction of natural aggregates (benefits), but with associated burdens (for instance, the energy consumed for the carbonation process, or the production of cement required by the new concrete). Those benefits and burdens should be attributed to the life cycle of the "new" CRCA-containing concrete (module D) and be clearly distinguished from the environmental impacts of the original CRCA-containing concrete, to avoid accounting for environmental burdens or benefits before they occur.

4.5 Multifunctionality

- Clearly **inform the approach used to address multifunctionality**, employing standard LCA terminology [21, 30]:
    - o **System expansion:** when impacts are declared for all functions together, with no allocation performed (see Fig. 10).
    - o **Substitution:** when impacts are declared for the CRCA or CRCA-containing product by subtracting the equivalent functions of the reference system (Fig. 11).
    - o **Partitioning (allocation):** when impacts are divided among the different functions; in this case, the criteria used for partitioning and the corresponding allocation factors should be clearly reported (see Fig. 12).

- In the case of **partitioning/allocation**, product systems must first be expanded to ensure that the division of the total impact is consistent [37].
- Applying **system expansion can be challenging**, especially when multiple multifunctional processes are included within the system boundary [37]. However, for processes typically involved in the production of CRCA or CRCA-containing products, this is usually not a major issue, since the CO_2 capture step does not usually affect the quantity and properties of the co-products being produced by the CO_2-emitting process (for example, a steel mill with or without carbon capture still produces the same amount and types of steel and steel slags), and likewise, the sorting of concrete waste does not affect the products of the waste-generating process.
- In case of substitution, **the choice of the substituted product should be coherent with the goal and the context of the study**. For example, in some places, using RCA (instead of NA) is mandatory for some applications [66]; therefore, in those cases, CRCA should be compared to RCA and not NA. When multiple substitution options are available, a sensitivity analysis is recommended to evaluate the impact of this choice on the LCA results. In any case, the substituted product should be representative of the relevant technological and geographical context, and must not be selected to maximise the apparent environmental benefits of CRCA, as this would bias the LCA results and undermine their credibility.
- **Ensure consistency** in the chosen approach for handling multifunctionality. For instance, if CRCA is credited with avoiding CO_2 emissions (under a substitution approach in an attributional LCA), it should also account for the associated burdens of carbon capture, pressurisation, and transportation.
    - o Similarly, if declaring benefits and burdens beyond the product's service life, ensure that flows are not accounted twice. For instance, if CRCA has been credited during its first use for avoided CO_2 emissions, it should not account for this benefit when considering its recycling after its end-of-life.
- When performing partitioning/allocation, ensure that impacts are assigned only to products, not waste streams. **End-of-waste criteria** should be

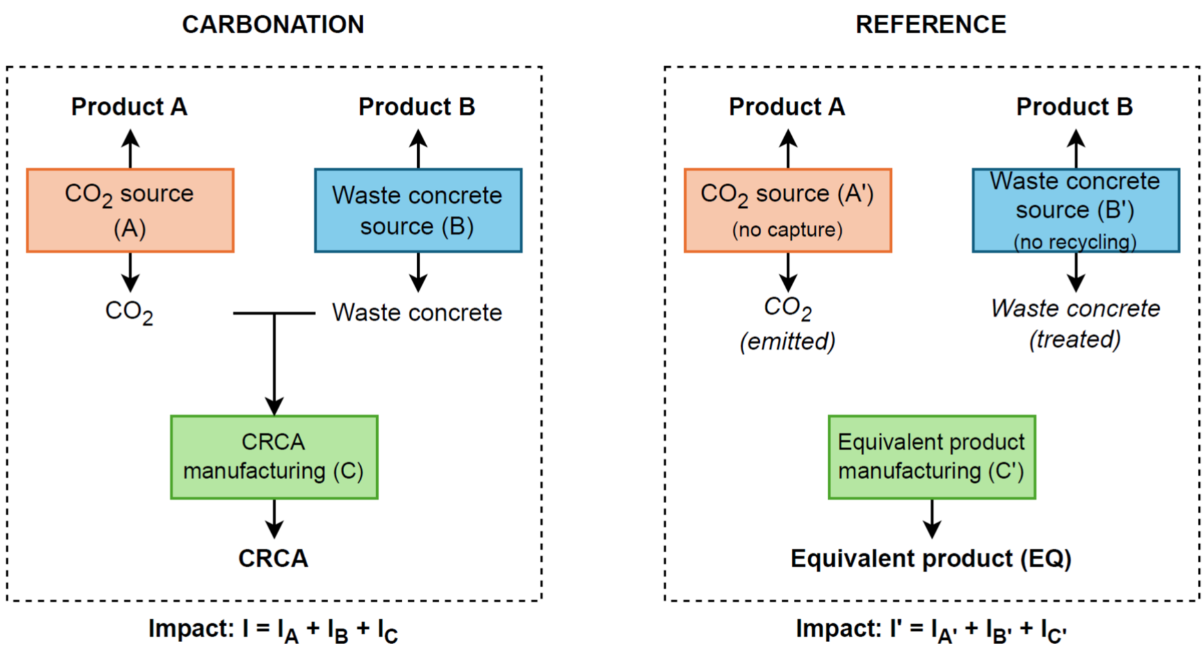


Fig. 10 Schematic representation of system expansion for the carbonation-based system producing CRCA, and the reference system producing equivalent products (based on [19])

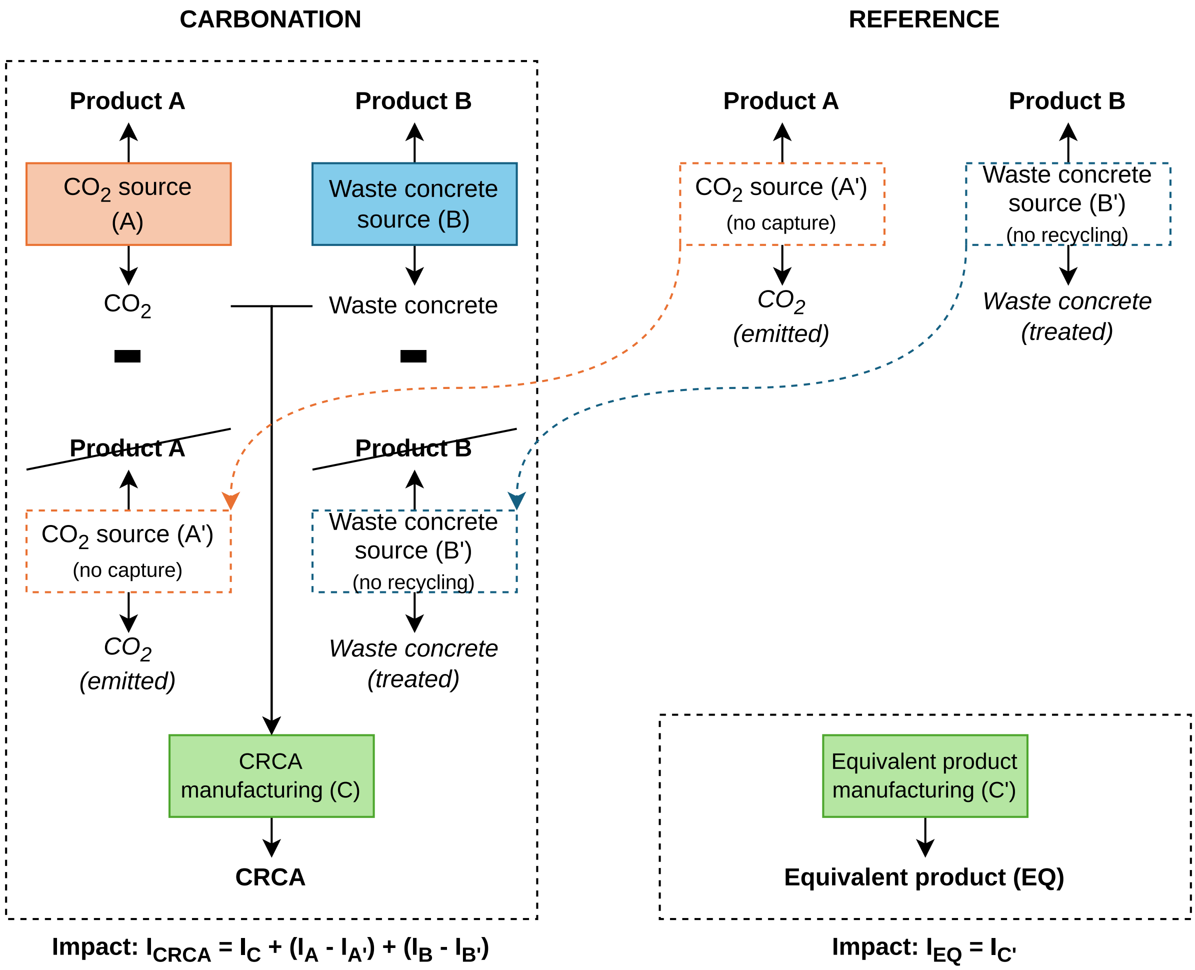


Fig. 11 Schematic representation of substitution for the carbonation-based system producing CRCA, and the reference system producing equivalent products (based on [19])

applied to determine whether a given flow should be considered a secondary material (which has reached end-of-waste status) or a waste stream [32]. Note that these criteria may vary regionally and generally include chemical properties (e.g. leaching of contaminants, pH, sulphate content), and sometimes physical characteristics (e.g., particle size distribution, density, fines content), as well as quality/performance (e.g., crushing resistance, composition variability).

4.6 Life cycle inventory

- **Consider and report the actual CO_2 uptake** by CRCA (not the theoretical maximum), along with the **method used to determine it**. Due to the significant dependence on the RCA composition, primary data are much more reliable than literature data, which should be used only as a last resort and applied cautiously.
- For LCA studies performing allocation, **deduct the CO_2 already bound in RCA** at the system boundary (for example, CO_2 bound through natural or passive recarbonation of concrete during its previous service life or RCA stockpiling) from the

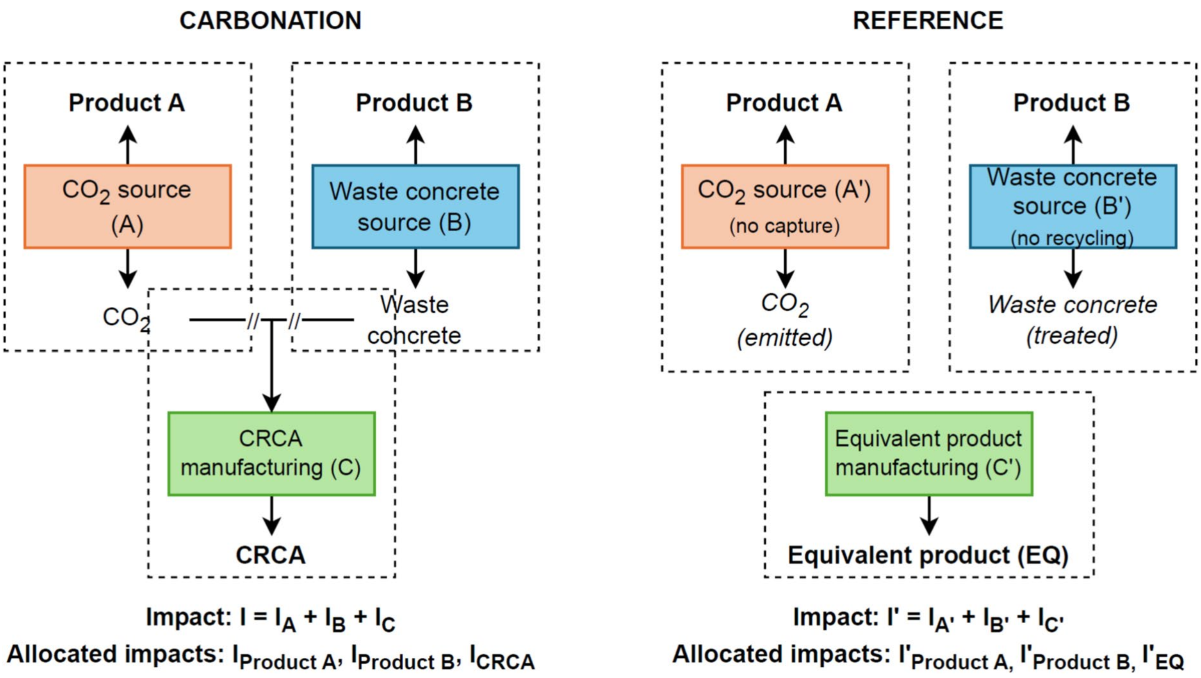


Fig. 12 Schematic representation of partitioning for the carbonation-based system producing CRCA, and the reference system producing equivalent products (based on [19])

CO_2 uptake measured in the CRCA. This approach ensures that only the CO_2 uptake induced by enforced carbonation is accounted for. Natural (passive) carbonation of concrete over its previous service life should be allocated to the primary product (concrete structure), while natural carbonation during RCA stockpiling may be counted as carbon removal (with its allocation depending on the system boundary), but it should always be distinguished from enforced carbonation.

- **Report the type(s) of CO_2 used** (fossil, geogenic, biogenic, or atmospheric) – in some processes (such as the coprocessing of municipal solid waste), CO_2 may be partly fossil and partly biogenic. **Only biogenic or atmospheric CO_2 should be modelled as CO_2 removals** [19, 36] (see Fig. 13). Natural carbonation utilises atmospheric CO_2 and should therefore be modelled as carbon removal.
- **Consider all relevant mass and energy flows** within the defined system boundary in the LCI, including the energy required for carbonation and CO_2 emissions due to storage inefficiency (since not all CO_2 injected during enforced carbonation remains stored).
- **Report the relevant metadata**, including parameters of the enforced carbonation, and **provide LCI data** whenever possible.
- **Use primary data** to model foreground processes whenever possible and **report secondary LCA data sources** used for background processes.
- Where relevant, **account for uncertainties** (for example, in transportation distances if multiple waste sources could be used).

4.7 Life cycle impact assessment

- **Always assess Global Warming Potential** using a 100-year timeframe (GWP-100), following the latest IPCC methodology.
- For LCA studies that include processes subject to **long-term natural recarbonation**, use **dynamic LCA** [56, 57] to avoid overestimating the climate benefit of natural recarbonation [58]. Use time-dependent LCI that includes the timing of GHGs

emission/sequestration, and dynamic characterisation factors to account for the actual persistence of the GHGs in atmosphere.

- It is advisable to **assess other relevant impact categories** to analyse potential trade-offs (for example, cumulative energy demand for energy-intensive processes).
- Clearly **distinguish between actual and avoided impacts**, presenting separate figures to enable comparison [35].
- It is recommended to **present impact results by life cycle stage** to enhance comparability.

4.8 Interpretation

- The term **carbon-negative** should be used only if the GWP is < 0 without substitution effects, which requires the storage of biogenic or atmospheric CO_2 [35].

5 Contribution and sensitivity analyses

- should be conducted to identify critical points and to test the robustness of the results.
- All assumptions must be clearly stated.

6 Conclusion

The contribution of carbonated construction products to climate change mitigation through permanent CO_2 storage cannot be evaluated solely based on their CO_2 uptake. A comprehensive Life Cycle Assessment (LCA) is necessary to account for the full spectrum of environmental impacts, including those associated with CO_2 capture, transport, and the enforced carbonation itself. Our review of published LCA studies on carbonated recycled concrete aggregates (CRCA) reveals significant methodological inconsistencies across key aspects such as functional unit definition, system boundary selection, CO_2 uptake estimation, CO_2 source consideration, handling of multifunctionality, and the distinction between avoided greenhouse

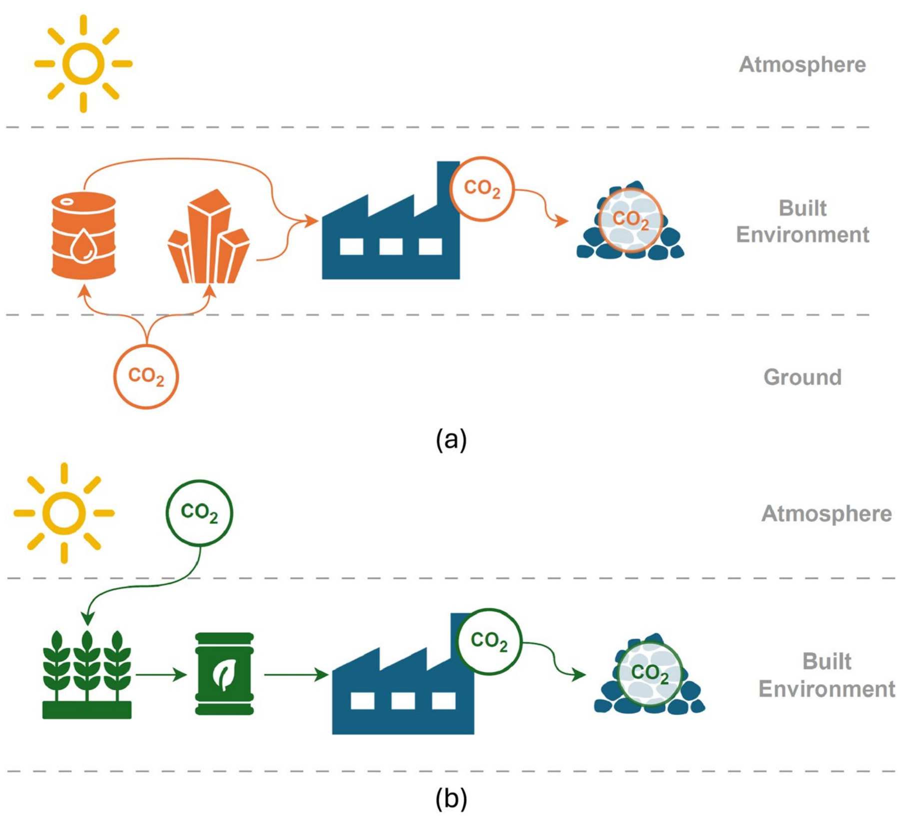


Fig. 13 Modelling of CO_2 flows permanently stored in carbonated products: (**a**) fossil or geogenic CO_2 emissions are stored in the carbonated product and therefore do not reach the atmosphere (GWP = 0); (**b**) biogenic CO_2 has been previously removed from atmosphere and remains permanently stored in the carbonated product (GWP = − 1), which also applies to CO_2 from direct air capture and natural carbonation

gas emissions and actual CO_2 removals. These divergences limit the comparability, reproducibility, and transparency of LCA results, and may lead to misinterpretations—especially regarding claims of "carbon negativity".

To address these issues, we have proposed a set of structured recommendations aligned with established LCA standards and CCUS-specific guidance. These recommendations aim to support more robust and harmonised LCA studies by promoting methodological clarity, appropriate handling of CO_2 flows, and clear communication regarding the meaning of negative GWP results. While these recommendations were developed with a focus on CRCA, they are equally applicable to other carbonated construction products. We expect that their adoption will contribute to enhancing the quality and credibility of LCA studies in this field, thereby supporting informed decision-making. As economic feasibility is crucial for the adoption of carbonated products, similar guidelines for performing techno-economic assessments should be developed, considering the inherent multifunctionality of carbonated products and the required integration between techno-economic and life cycle assessment.

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Declarations

Conflict of interest The authors have no conflict of interest to declare.

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