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LCA OF WASTE MANAGEMENT SYSTEMS

Life cycle assessment on construction and demolition waste recycling: a systematic review analyzing three important quality aspects

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Abstract

Purpose Life cycle assessment (LCA) is increasingly being applied to construction and demolition waste (CDW) recycling. But what is the current state of LCA studies on CDW recycling? In the context of circular economy, several aspects become important in LCA, such as avoided impacts and consideration of the quality of recycled materials. The aim of this study is to identify inconsistencies and best practices, and then provide recommendations for future LCA studies focusing on CDW recycling.

Methods We conducted a systematic literature review on 76 journal articles. First, a general mapping of the selected studies was performed including the temporal and geographical distribution, and a bibliometric analysis to capture the linkages between the studies. Within the LCA content-based analysis, an in-depth assessment of three important quality aspects: *(1) quality of the study* based on the applied LCA methodology, *(2) inclusion of material quality* in LCA, and *(3) data quality* considering sensitivity and uncertainty analyses, was carried out. Major LCA components such as functional unit (FU), software, database, system approach (attributional or consequential), allocation method, life cycle impact assessment, and interpretation were evaluated. A special emphasis was placed on avoided impacts and the inclusion of recycled material quality in the LCA.

Results and discussion In this review, it was found that many essential elements of LCA were missing or not implemented correctly. For example, in the definition of FU, some studies did not mention any FU, others defined an invalid FU, and most of the studies defined a uniform FU, which was most likely confused with the reference flow. The main problem observed is the lack of transparent reporting on the different elements of LCA. Regarding avoided impacts, for instance, only 13 studies reported the avoided materials and their substitution coefficients. Also, 6 studies used the term "virgin material" for avoided impacts without further information, which is a very broad term and difficult to interpret. Furthermore, only 12 studies included the quality of recycled material in the LCA.

Conclusion To obtain reliable LCA results, the practitioners should follow the principal LCA methodology and peer-reviewers should ensure the proper implementation. In CDW recycling, the differentiation between downcycling and recycling is essential; therefore, the quality of recycled materials should be included in the LCA. Considering inconsistent implementation of avoided impacts, a standardized and well-defined avoided impact framework is suggested to be developed to improve the quality and reliability of future LCA studies.

Keywords Life cycle assessment · Circular economy · Construction and demolition waste · Recycling · Downcycling · Product quality · Literature review

1 Introduction

The construction industry is a leading industry in the world considering both its role in economic development, and the environmental impact caused by it. In 2018, 35.9 wt% of the total waste produced in Europe was generated by the construction industry, turning it into the largest contributor to waste production (Eurostat 2021). On the one hand, a large

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amount of consumed resources and waste generated by the construction industry causes environmental stress; however, on the other hand, it has great potential in the context of the European circular economy (CE). The role of the construction industry within the CE was highlighted in the European Waste Framework (Directive 2008/98/EC) in 2018. This framework introduced a target of 70% as a recovery quote for the construction and demolition waste (CDW) by 2020 for the European member states. Most of these countries have already achieved the target; for instance, in Germany, the CDW recovery rate was 88% in 2019 (Destatis 2021). Although Germany's CDW recovery rate is relatively high, 75% of recovered CDW is labeled as downcycled, which means that the recycled products end up with lower quality compared with the original products (Volk et al. 2020). In CDW recycling, downcycling is a growing problem that requires awareness, both through technical development for a greater quantity of high-quality recycled aggregates (RAs) production and through quality standards that need to be set through policy instruments.

The differentiation between downcycling and recycling and the importance of achieving high-quality recycled materials have been emphasized within the CE, which has gained increasing attention over the past years by academia, politics, and industries. CE itself has various definitions, for instance, Kirchherr et al. (2017) defined CE as "an economic system that replaces the "end-of-life" concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro, meso, and macro level, with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations" (p. 229). On the one hand, CE includes the circularity of materials, components, and products, and on the other hand, CE may also include effects on the economy, environment, and society. Assessing these different aspects within CE is complex (Moraga et al. 2019). Life cycle assessment (LCA) is a widely used tool for quantifying environmental impacts and is recommended to be included in CE assessment (Pomponi and Moncaster 2017; Scheepens et al. 2016; van Stijn et al. 2021). Even though LCA has a standardized framework by the International Organization for Standardization (ISO 14040 2006; ISO 14044 2006), it lacks sufficient guidance when it comes to the allocation approach (Majeau-Bettez et al. 2018; Sandin et al. 2014; Schaubroeck et al. 2021; Schrijvers et al. 2016). Within CE, especially in recycling systems, the applied allocation approach can greatly affect the results. In addition, closed-loop and open-loop recycling play a crucial role within the CE context, and not taking this distinction into account in LCA can lead to a deterioration of the recycled material pool (Di Maria et al. 2018; Glogic et al. 2021; Koffler and Florin 2013). Similar to many other fields, LCA has been used in the CDW field by many researchers (Borghi et al. 2018; Butera et al. 2015; Guignot et al. 2015). Additionally, several literature reviews have focused on the LCA in the construction industry. For instance, Zhang et al. (2019a) reviewed LCA studies on recycled aggregate concrete (RAC), covering the effect of the mixture design method, functional unit, allocation, and type and distance of transportation. Wu et al. (2014) also reviewed articles on LCA in concrete, mainly focusing on its use and its end-of-life (EOL) phases. Ghisellini et al. (2018) assessed the economic and environmental costs and benefits of the CE in the construction and demolition sector. Similarly, Lopez Ruiz et al. (2020) reviewed the CE applications in the CDW sector. A scientometric systematic review on LCA applications in CDW was conducted by Chen et al. (2021a), undertaking a science mapping including keyword coherence analysis and a general overview on LCA applications. Bovea and Powell (2016) conducted a detailed review of the applied LCA framework for CDW management, mainly assessing the four steps of LCA. Finally, Mesa et al. (2021) performed a systematic review on LCA studies focusing on CDW and categorized the studies covering their aim, methodology, and impact categories. Although some reviews have focused on CDW management and LCA, a detailed overview of whether and how recycled product quality is included in LCA is lacking. This is a highly important issue considering the role of LCA within CE. At the same time, it is important to address the quality of the LCA study itself through compliance with ISO 14040/44 (2006). To tackle the quality issue in LCA studies focusing on CDW recycling, we performed a comprehensive and critical review on peer-reviewed journal articles. First, a general mapping of LCA studies on CDW recycling was performed including the temporal and geographical distribution and bibliometric analysis. Second, a content-based analysis was performed focusing on three main quality aspects, (1) *quality of the study*: based on applied LCA methodology by identifying the essential components of LCA, (2) *material/product quality*: how the quality of input waste or end products were included in the LCA, and (3) *data quality*: transparent reporting of primary data and whether sensitivity and uncertainty analyses were performed. The overreaching aim of this study is to identify the problematic areas in LCA methodology and reveal the best practices to provide recommendations for future studies.

1.1 Research focus

In this review, we focused on two main areas:

Scientometric analysis: a general mapping to get an overview on:

- The temporal and geographical distribution of the selected articles.
- Bibliometric analysis including the article citation, keyword co-occurrence, and journal occurrence. The arti-

cle citation analysis provides information on the links between the articles and their citation number. Keywords and journal occurrence analyses give an overview of the most frequently selected keywords and the main journals in which the studies were published.

LCA content-based analysis: The compliance of the LCA studies with ISO 14040/44 (2006) was assessed. The most relevant components of the LCA methodology were selected for in-depth analysis. The following research questions were aimed to be answered:

RQ1. Which functional units (FUs) were used in LCA studies? What are the main problems with the selected FU in the reviewed studies?
RQ2. Whether the input CDW and output (mainly RAs) quality was mentioned and considered? And if so, how and to what extend was the quality aspect included in the LCA?
RQ3. Which system approach was used, attributional vs. consequential, not only from an EOL perspective but also the selected databases for modeling background processes?
RQ4. Whether and to what extent the avoided impacts were included in the LCA, and how do they affect the results?
RQ5. Whether sensitivity and uncertainty analyses were conducted, and which aspects were included in the analyses.

The remainder of this paper is structured as follows: in Sect. 2, the review methodology is described; in Sect. 3, the results are presented and discussed; and in Sect. 4, we draw a conclusion and provide some recommendations for future studies.

2 Methods

A systematic literature review (SLR) is a comprehensive, reproducible, and rigorous method (Minunno et al. 2021; Siddaway et al. 2019), that provides reliable findings on specific research questions through assessing all relevant available literature (Snyder 2019). In this study, we followed the PRISMA statement (Page et al. 2021), and the search strategy is explained in Sect. 2.1.

2.1 Search strategy and selection process

We performed the SLR in four main steps: identification, screening, eligibility, and inclusions. A detailed explanation of each step is given in the following section (summarized in Fig. 1).

Identification: Following the aim and scope of the study, the search strings were determined based on three main topics: LCA, CDW, and recycling. Because using CDW as a keyword could cause exclusion of relevant literature, it was decided to use "construction" and "construction and demolition" keywords instead. Three databases, Scopus, Web of Science, and Science Direct, were selected and the keywords used for each database are given in Table 1. The search was performed in November 2021, and only literature written in English was included. After removing duplicates, a total of $n = 1041$ articles were included in the screening process.

Screening: Screening was performed in two steps: title and abstract, following the exclusion criteria as shown in Fig. 1.

Eligibility: The last screening was done based on the full-text of the articles ($n = 128$), and the studies that are not an LCA, out of scope, and not assessing recycling process were excluded. In the full-text screening, the selected articles were limited to peer-review articles. This criteria had not been set before; however, after the full-text screening, it was seen that similar content was used for conference proceedings or book chapters

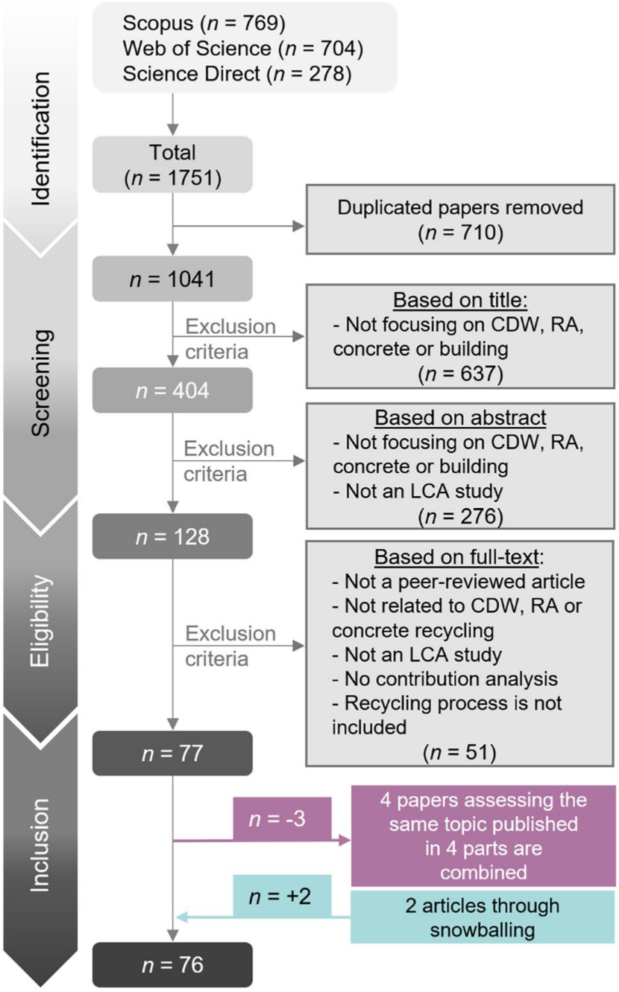


Fig. 1 Flow diagram of the SLR process

Table 1 Search strings used for each database

Database	Search strings
Scopus	TITLE-ABS-KEY ((**LCA** OR "**Life cycle assessment**") AND ("**construction**" OR "**construction and demolition**") AND (**recycl***))
Web of Science	TOPIC: (((**LCA** OR "**Life cycle assessment**") AND ("**construction**" OR "**construction and demolition**") AND (**recycl***)))
Science Direct	Title, abstract, keywords ((**LCA** OR "**Life cycle assessment**") AND ("**construction**" OR "**construction and demolition**") AND (**recycle** OR **recycling**))

or journal articles by the same author. In order to prevent double counting, it was decided to include only peer-reviewed journal articles. After the eligibility assessment, a total of 77 articles were included for further assessment. In the last step, 4 articles written by Coelho and Brito (2013a, b, c, d) were combined as one study, because these studies assess the same CDW recycling plant from LCA and LCC aspects which were published in four papers. In addition, 2 articles were included through snowballing, as described in detail by Kroell et al. (2022). At the end, 76 articles were selected for in-depth analysis.

3 Results and discussion

3.1 Scientometric analysis

Figure 2 presents the geographic and temporal distribution of selected articles. The majority of selected articles were published in 2018 ($n = 13$) and 2020 ($n = 17$). Italy and China had the highest number of articles ($n = 11$), followed by Spain ($n = 8$).

A bibliometric analysis was performed using VOSviewer, which is a software tool for creating bibliometric networks with various visualization options based on different parameters such as bibliographic linkage, co-citation, or co-authorship relations (van Eck and Waltman 2010). In this review, VOSviewer was used to visualize and analyze the selected articles in a bibliometric form in three levels: article co-citation, keyword co-occurrence, and journal occurrence. An article-level co-citation analysis was selected to assess the citation number of selected articles and identify the links between them. We chose a co-citation analysis to determine whether the results of the selected studies are recognized by each other and to represent their degree of relatedness. The co-citation analysis is shown in Fig. 3, in which the size of the nodes corresponds to the number of

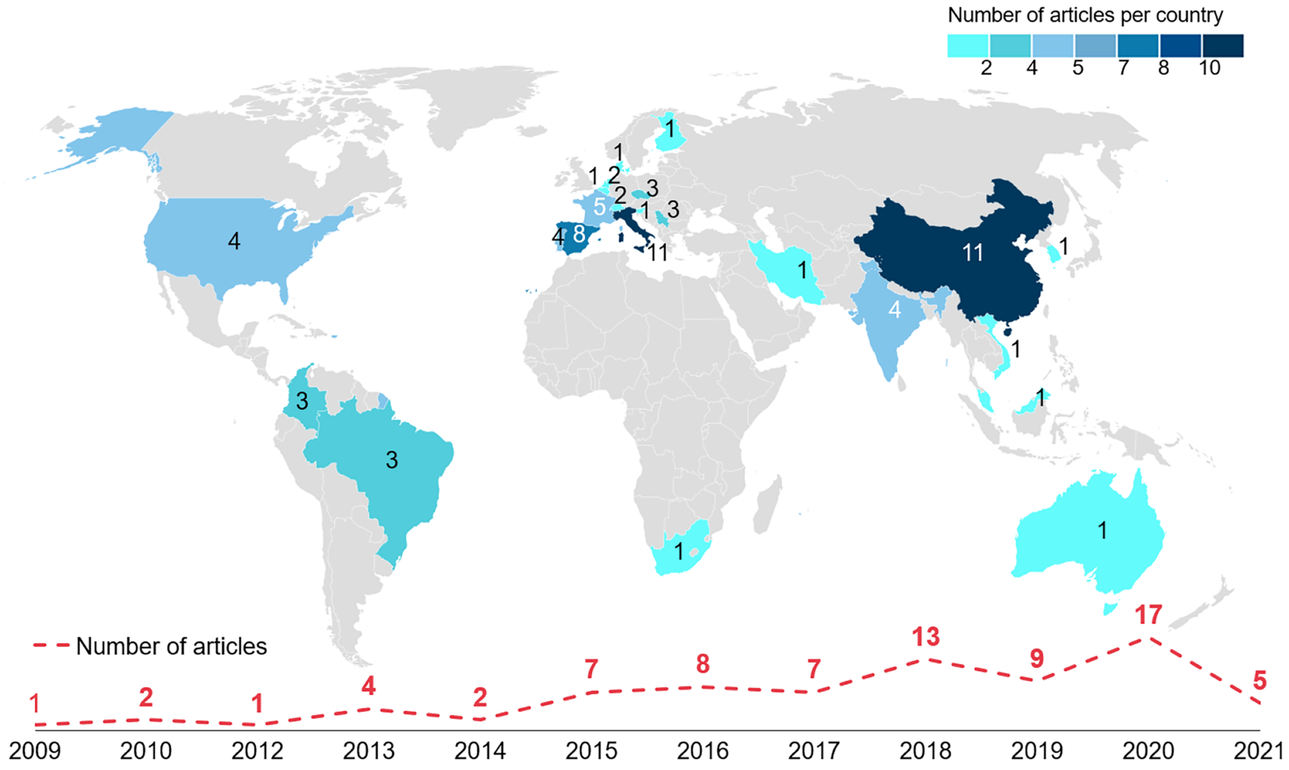


Fig. 2 Geographical and temporal distribution of the selected articles

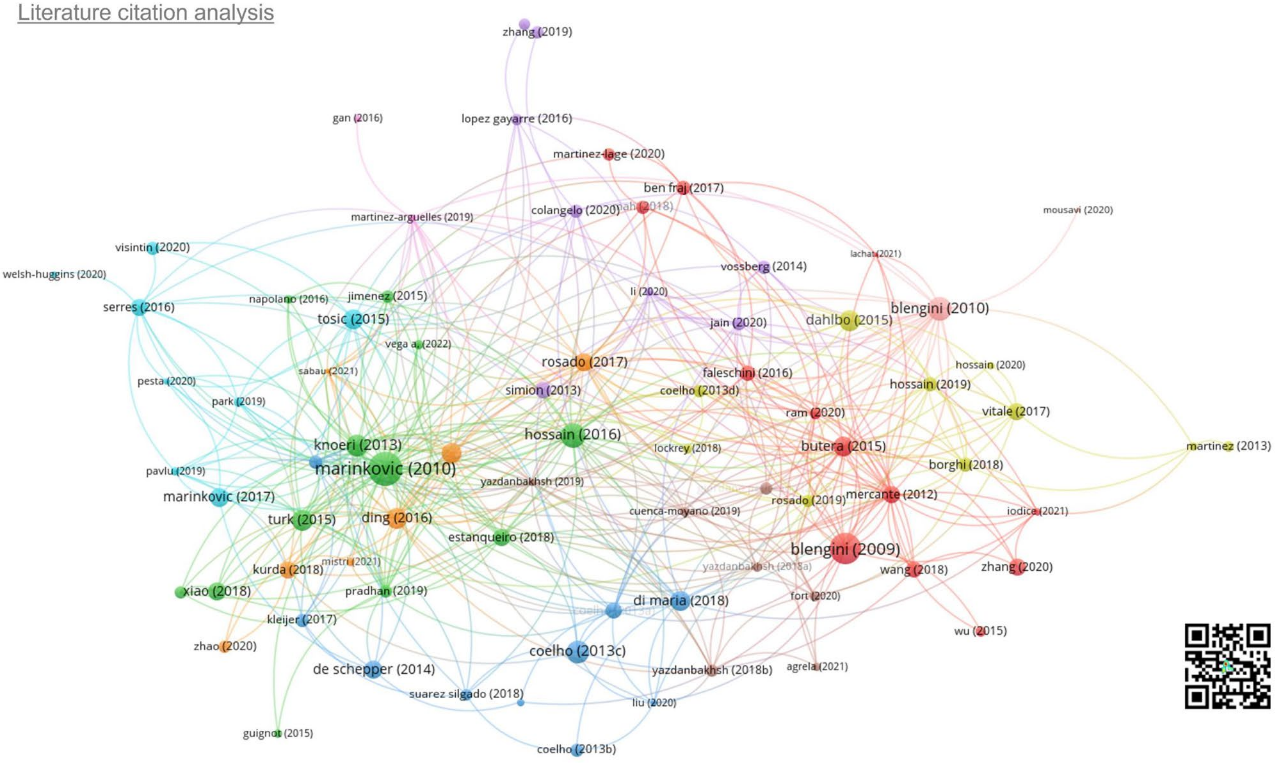


Fig. 3 Overview on the literature citation analysis on a document level (access through this link https://tinyurl.com/2abbhzvs) using VOSviewer. Different colors indicate different clusters, and the size of circles indicates the frequency

citations, the distance between nodes corresponds to the tendency for studies to be jointly cited by other studies, and the lines correspond to the presence of a citation in both directions. Based on the co-citation analysis, Marinković et al. (2010) have the highest number of links ($n=45$) followed by Blengini and Garbarino (2010), Hossain et al. (2016), and Knoeri et al. (2013).

Similarly, a keyword co-occurrence analysis was performed applying author keywords option in VOSviewer, in which only the keywords that are mentioned at least 3 times were included. "Life cycle assessment" is the most mentioned keyword, in total 58 times including different variations ("life cycle assessment (LCA)," "LCA"), followed by "construction and demolition waste" and "CDW" ($n=27$). Lastly, the journal overview was assessed. The majority of the selected articles ($n=22$) were published by the *Journal of Cleaner Production*, and it is followed by the *Journal of Waste Management* and the *Journal of Resources Conservation and Recycling*. The keyword and journal occurrence analyses are presented in the Appendix (Fig. 10).

3.2 LCA content-based analysis

In this section, we selected the most relevant components of the LCA methodology, rather than analyzing all LCA steps. By doing so, we were able to examine and discuss each aspect in more detail. The LCA components that we focused on were selected based on their importance in LCA, their relevance within the CE concept, and the critical points that we observed in the reviewed literature. In the following section, the results for each selected LCA component: FU, CDW input composition and end product quality, data source, software and database, system approach, allocation method, life cycle impact assessment (LCIA) method, and sensitivity and uncertainty analyses, are presented in detail. The results are generally presented in an aggregated way, and only in the discussion of an argument, relevant study results are commented individually.

In addition to environmental impact assessment, economic and social aspects were also evaluated in some studies, as shown in Appendix Table 5, 21% of the reviewed studies included cost impact in addition to LCA. Only one study (Iodice et al. 2021) applied life cycle sustainability assessment (LCSA) including all three aspects: environmental, economic, and social. This overview highlights especially the need for further research on the social aspect.

3.2.1 Functional unit

FU is defined as "quantified performance of a product system for use as a reference unit" according to ISO 14040/44

(2006) and should be set to align with the goal and scope of the study. The selection of the FU is critical because it provides the basis for quantifying all inputs and outputs, enables appropriate interpretation of results, and allows comparison of LCA results based on equivalent functional performance of different processes, products, or systems (Panesar et al. 2017). Within the reviewed studies, except for 5 articles, the FU was reported. A summary of defined FUs in selected articles is presented in Fig. 4; in general, 3 different focus groups were identified: CDW or aggregate, concrete, and building. In two articles, a non-relevant definition of FU was observed. For instance, Estanqueiro et al. (2018) mentioned that FU was not defined due to the quality issue which is stated as "coarse natural and recycled aggregates may not present the same performance over their life cycle (p.5)"; however, the results were compared per ton of aggregate. The reasoning is not relevant as the aim of FU is to enable the comparison. Another malpractice example was observed in Gan et al. (2016), in which the authors set the FU as "1 kg atmospheric emissions per 1 kg for natural aggregate (NA) and RA (p.77)", which is an inaccurate description.

Studies that focus on CDW recycling or aggregate production had either defined the FU as mass of CDW handled, input-based (mainly as 1 ton of CDW handled), or as mass of RA produced, output based (mainly as 1 ton of RA produced). Since there is usually more than one end product group in CDW recycling, one way to avoid misunderstanding is to include both the input CDW and end products in the FU, as applied by Di Maria et al. (2018), Zhang et al. (2018), Zhang et al. (2019b), Paula Junior et al. (2021), and Vossberg et al. (2014). This is a useful approach to increase the transparency and comparability of the studies. In addition, including the CDW composition and specification in the FU is relevant as the CDW input quality has a big impact on the recycling efficiency and end product overview. Similarly, when an output-based FU is set, RA quality and application area should be stated. As presented in Fig. 4, majority of studies defined a unitary FU, where waste or product compositions were not included.

For the articles focusing on concrete, where mainly a comparative LCA between natural aggregate concrete (NAC) and RAC is conducted, compressive strength (MPa) or the specific weight of concrete was mentioned in the FU, except for 8 studies. A different approach for defining the FU for RAC vs. NAC comparison was applied by Mistri et al. (2021), where first the environmental impacts were calculated per m^3 of concrete, but then, the results were divided by the corresponding compressive strength. FU selection in the comparison of RAC and NAC was also pointed out by Zhang et al. (2019a), and the authors concluded that using the volume of concrete as FU can lead to inaccuracy as the compressive strength of concrete is observed to be decreased

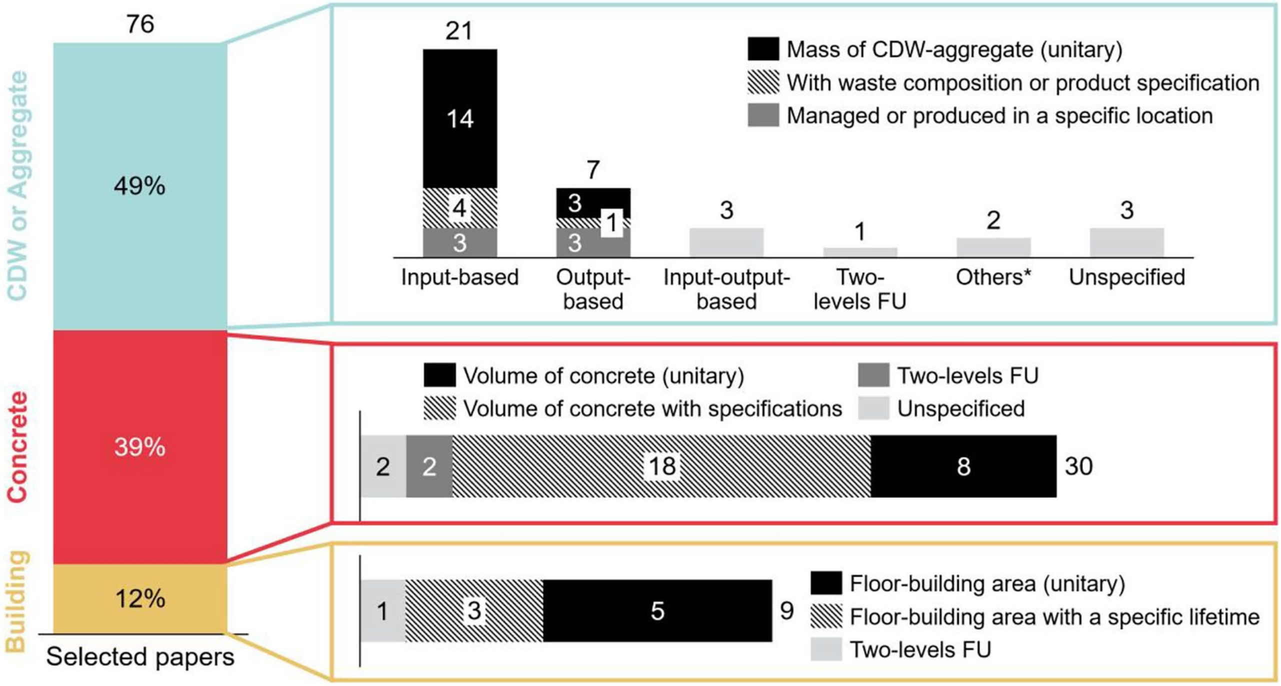


Fig. 4 A summary on the FUs mentioned in the selected studies is presented. The papers are grouped into three focus groups: CDW or Aggregate, Concrete, and Building. Within the CDW or Aggregate group, input- and output-based analysis, and information on the FU, such as unitary or further specifications, are given. In the Others* category non-relevant definitions of FU were included. Two levels of FU refer that within the same study, two different FUs were assessed

with the increased RA input. The authors concluded that combining volume and strength while setting the FU is a convenient approach, but also added that benchmark methods to define FU aiming to avoid the differences of LCA studies and increase the comparability of studies is urgently needed (Zhang et al. 2019a).

Agrela et al. (2021) and Lachat et al. (2021) set two different FUs with two different system boundaries to assess (1) the impact of RA produced though the recycling process and (2) the impact of end products, in this case, road pavement production using RA. This is a convenient and helpful approach especially when the focus of the study is on RAC. In the review, it was observed that the majority of literature evaluating the environmental impacts of RAC does not provide detailed information on the recycling process or on the attribution of environmental impacts to RA which is used in concrete production. In order to increase transparency, including two levels of FU, where impacts per RA production will also be reported separately, was found to be helpful. Marinković et al. (2017) followed a different approach, where again the main focus was on concrete, and performed a sensitivity analysis on selected FU. A comparison was done with FUs of 1 m^3 concrete mixes with a specific strength and 1 m^3 of concrete mixes including strength, serviceability, and durability. The authors concluded that including the serviceability and durability did not change the results.

The main issue observed within the reviewed papers in terms of FU is the misunderstanding and most probably confusion of FU with reference flow. Reference flow is defined as “measure of the outputs from processes in a given product system required to fulfill the function expressed by the FU” by ISO 14044 (2006). FU is the quantified performance of the system, which should include relevant information to enable comparability. Thus, it is essential to include important information on the assessed system, such as CDW composition and the end products including their quality and possible application areas. A review done by Laurent et al. (2014) on LCA studies on solid waste management systems highlighted the same issue, where the waste composition was left out in the FU, and FU was mostly confused with reference flow. Through this review, we observed a similar issue, and especially for LCA studies focusing on CDW recycling, not only the input waste composition but also the end product overview is essential to enable comparison and correct interpretation of results by preventing possible misunderstandings.

3.2.2 CDW input composition and end product quality aspect

CDW input composition CDW input quality has a big impact on recycling efficiency. For instance, if the CDW is selectively demolished, compared to a mixed CDW, a lower energy demand will be observed to achieve similar end products. In addition, not only selective or non-selective demolition, but also detailed waste composition is important (Hyvärinen et al. 2020; Müller and Martins 2022; Vegas et al. 2015). According to reviewed articles, it is seen that 50% of the studies did not give any information on the composition of the input CDW. Only 16% of the studies included detailed information with percent division of different material and waste groups. The remaining studies indicated the type of demolition or whether the waste is mixed, brick, or concrete based (see Fig. 5).

As previously touched on Sect. 3.2.1. “Functional unit,” Agrela et al. (2021) compared the different quality of RAs coming from selectively and non-selectively demolished waste without including the demolition process itself. Similarly, Ben Fraj and Idir (2017) compared RAC produced by 3 different RA qualities, one sourced by mixed CDW and the others sorted CDW, but again the demolition process was not included. Selective demolition requires higher energy consumption compared to non-selective demolition (Coelho and Brito 2013c; Iodice et al. 2021; Pantini and Rigamonti 2020); thus, comparing selective and non-selective

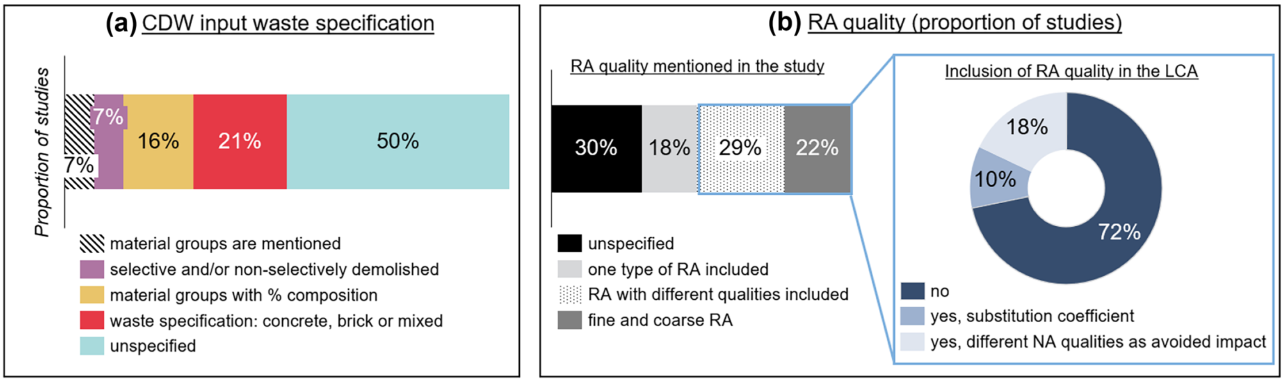


Fig. 5 A summary on (**a**) CDW input specification, and (**b**) RA quality mentioned in the scope of the study and its inclusion in the LCA

demolishing, the demolition process itself should be included in the system boundaries. When it comes to comparing two different recycling systems, it is important to include the CDW input quality in the FU to prevent misinterpretation of the results.

RA quality In CDW recycling, based on the input waste composition and applied recycling technology, a different quality of recycled products that are suitable for different application areas will be produced (Müller and Martins 2022). Overall, two main categories were observed: fine and coarse RA, where coarse RA is considered as high quality and can be used in concrete production; whereas fine RA is a low-quality aggregate to be used in road construction and as a filling material (Di Maria et al. 2018; Estanqueiro et al. 2018; Fořt and Černý 2020; Jain et al. 2020; Marinković et al. 2010; Pavlu et al. 2019; Tošić et al. 2015; Yazdanbakhsh et al. 2018; Zhang et al. 2019a, b). Within the selected articles, 30 articles mentioned the different quality of RA as end products through recycling, but only 12 of them included the quality aspect in the LCA (see Fig. 5). For instance, Agrela et al. (2021) mentioned four different quality levels of mixed RA, but for all four of them, the same NA impact was avoided as replaced material, which is contradictory. Similarly, Coelho and Brito (2013c) mentioned fine and coarse RA as end products, but again the same type and amount of NA was considered as avoided impacts. Likewise, Jiménez et al. (2015) stated coarse and fine RAs with different qualities, but in the LCA, mass allocation based on the same economic value was applied.

Articles focusing on concrete mainly included the quality of RAC and NAC in the LCA, through the concrete strength; however, only Colangelo et al. (2018) and Jain et al. (2020) made a distinction between fine and coarse aggregates. In total 15 articles did not touch on the quality of RA, and only 3 articles mentioned the RA quality and application area, but no information on the end product overview (e.g., fraction of different RAs) and the allocation of environmental impacts for RA was included. The main quality inclusion was done through the avoided NA that was replaced by RA. For instance, for a low-quality RA (or fine RA to be used in road construction or filling), sand or fine NA was considered as replaced material; on the contrary for high-quality RA (or coarse RA), gravel or coarse NA was taken as the avoided product (Colangelo et al. 2018; Di Maria et al. 2018; Faleschini et al. 2016; Guignot et al. 2015; Hossain et al. 2016; Jain et al. 2020; Pantini and Rigamonti 2020; Rosado et al. 2019; Zhang et al. 2019b). Blengini and Garbarino (2010) included economic allocation for three quality levels of RA, and for the avoided aggregates, again, three different quality levels of NA were considered. Borghi et al. (2018) followed a more comprehensive approach and included both the quality and the market demand for RAs, following the method introduced by Rigamonti et al. (2013). The same method was also used by Iodice et al. (2021), following the example of Borghi et al. (2018). This approach is relevant within life cycle thinking, especially with regard to the distinction between downcycling and recycling.

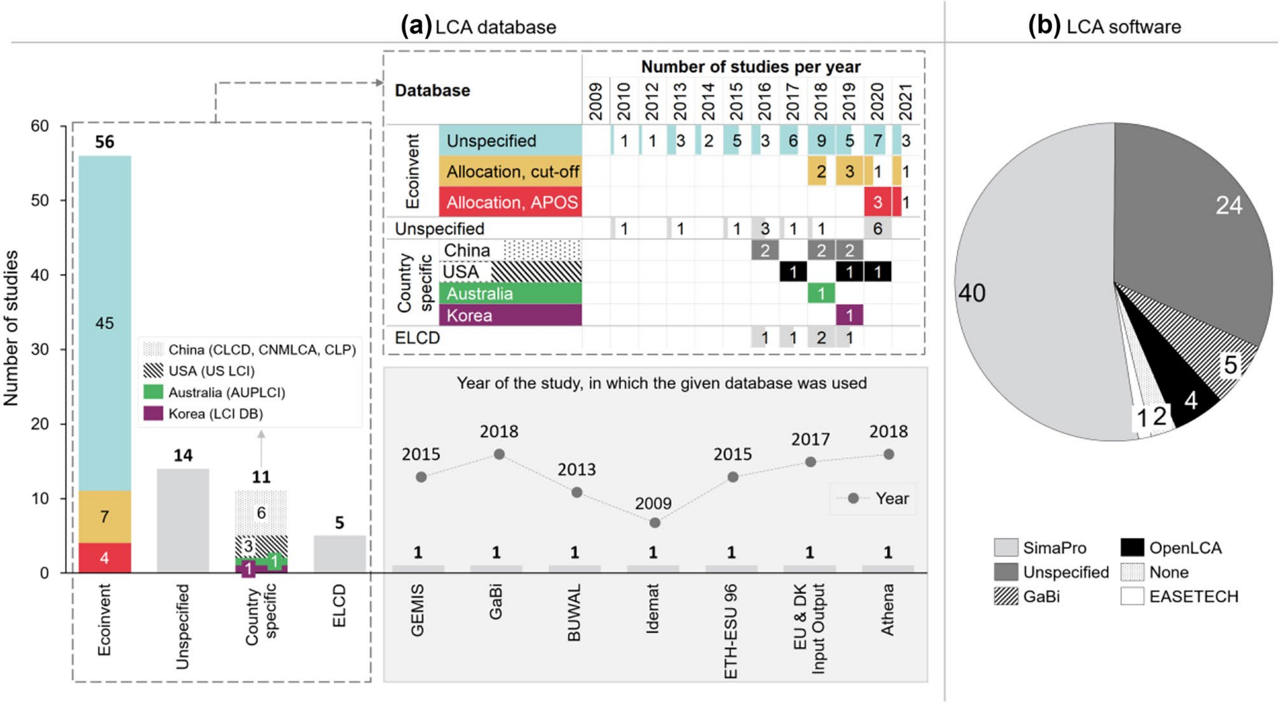
3.2.3 Data source, software, and database

SimaPro is the main software that was used for the LCA modeling, followed by GaBi, openLCA, and EASETECH. Twenty-four articles did not mention the software that was used, as shown in Fig. 6. More than 72% of the articles used the ecoinvent database for the background data. However, only 11 articles explicitly stated the ecoinvent database type, within them, 4 articles modeled with APOS and 7 articles with a cut-off system approach.

Based on the results, it is seen that 18% of the articles did not indicate the used database, which is essential for the transparency and traceability of the LCA study. As LCA is a data-intensive methodology, LCA practitioners generally collect primary data on selected activities, and generic data are mainly taken from life cycle inventory (LCI) databases (Steubing et al. 2016). As the generic data, or in other words background data, forms a big part of the LCA model, in addition to other parameters, the database selected should be reported transparently to enable reliable interpretation and possible comparison of LCA results. Pauer et al. (2020) studied the use of different databases, such as ecoinvent and GaBi, with different software combinations. The authors highlighted that different database-software combinations give different LCA results, except for global warming potential (GWP) impact and noted that the meaningful interpretation of results requires excellent knowledge on the studied system, database, and life cycle impact assessment (LCIA) methodology (Pauer et al. 2020). Not only the database (e.g., ecoinvent), but rather the system model followed by the selected database is essential (APOS, cut-off, or consequential). Saade et al. (2019) emphasized the importance of consistent model choices with the ecoinvent database.

Even though within LCA practitioners, the importance of databases for modeling background processes are beyond argument; still, it is seen that a big portion of LCA studies that we reviewed within this study did not mention the database and software used, 18% and 32% respectively (see Fig. 6). Transparent reporting is essential in LCA, where database and software used for modeling is a part of it, as these two parameters play a big role in the LCA model.

Majority of studies combined the site-specific data with databases and literature values. For the primary data, a lack of transparency and completeness is observed to be the main problem. For instance, not specifying the unit of electricity/diesel demand for the CDW recycling process was observed to be a common issue, which hinders to interpretation of the data, as it is not clear if it is input- or output-based.



Database		2009	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Ecoinvent	Unspecified		1	1	3	2	5	3	6	9	5	7	3
	Allocation, cut-off									2	3	1	1
	Allocation, APOS											3	1
Unspecified			1		1		1	3	1	1		6	
Country specific	China							2		2	2		
	USA								1		1	1	
	Australia									1			
	Korea										1		
ELCD								1	1	2	1		

Fig. 6 Overview on the number of (**a**) LCA databases and (**b**) LCA software used in the selected studies. The total number of databases is higher than the total number of papers, because in some studies more than one database was used. In the database overview, the proportions of mentioned system approaches, cut-off, and APOS, for the ecoinvent database, and county-specific databases are indicated with the given color code. In addition, an overview on the publication year of studies and database choice is presented

Similarly, the output overview and percent composition of different product groups, including by-products and waste produced, were missing. Transparent and complete primary data documentation is important and is observed to be lacking. An overview on the primary data that was available in the reviewed articles are presented in the Appendix (Table 6).

3.2.4 System approach (attributional and consequential)

Within the LCA, attributional LCA (ALCA) and consequential LCA (CLCA) are the two main methods that can be used. ALCA approach estimates the share of the global environmental burdens caused by a product, process, or system. On the contrary, CLCA evaluates the environmental consequences of a decision, looking from a wider perspective. Even though the ALCA approach is followed by the majority of LCA practitioners, the attention on the consequential approach has been increasing. At the same time, there is an ongoing discussion within the LCA community on when to use ALCA and CLCA, and the advantages and disadvantages of these two methods. These two approaches differ not only when it comes to allocation issue, but also the background database used (Bamber et al. 2020; Schaubroeck et al. 2021).

Only 13 articles explicitly mentioned the LCA approach that was applied in the article. Four articles (Butera et al. 2015; Hossain et al. 2016; Iodice et al. 2021; Turk et al. 2015) mentioned that the CLCA approach was followed, and 9 articles (Di Maria et al. 2018; Jain et al. 2020; Lockrey et al. 2018; Marinković et al. 2017; Martinez-Arguelles et al. 2019; Rosado et al. 2017; Rosado et al. 2019; Vega et al. 2020; Vitale et al. 2017) stated that the ALCA approach was applied. Sixty-three studies did not mention the applied LCA approach explicitly. Within these 63 studies, 7 of them specified the ecoinvent database type (APOS or cut-off) allowing to identify the system approach. However, for 56 studies, it was not possible to get any information on the system approach. A summary on the system approach and allocation method is shown in Fig. 7.

It is seen that attributional and consequential modeling definition is not clear within the LCA practitioners. For instance, Turk et al. (2015) stated the LCA approach as CLCA, due to the system expansion model being applied. However, the system expansion approach can also be used in ALCA, as a way to prevent allocation problem, as used by Di Maria et al. (2018). This issue has been highlighted by Schaubroeck et al. (2021), who mentioned that the system expansion approach can be used both for ALCA and CLCA. Within the LCA approach topic, not only the

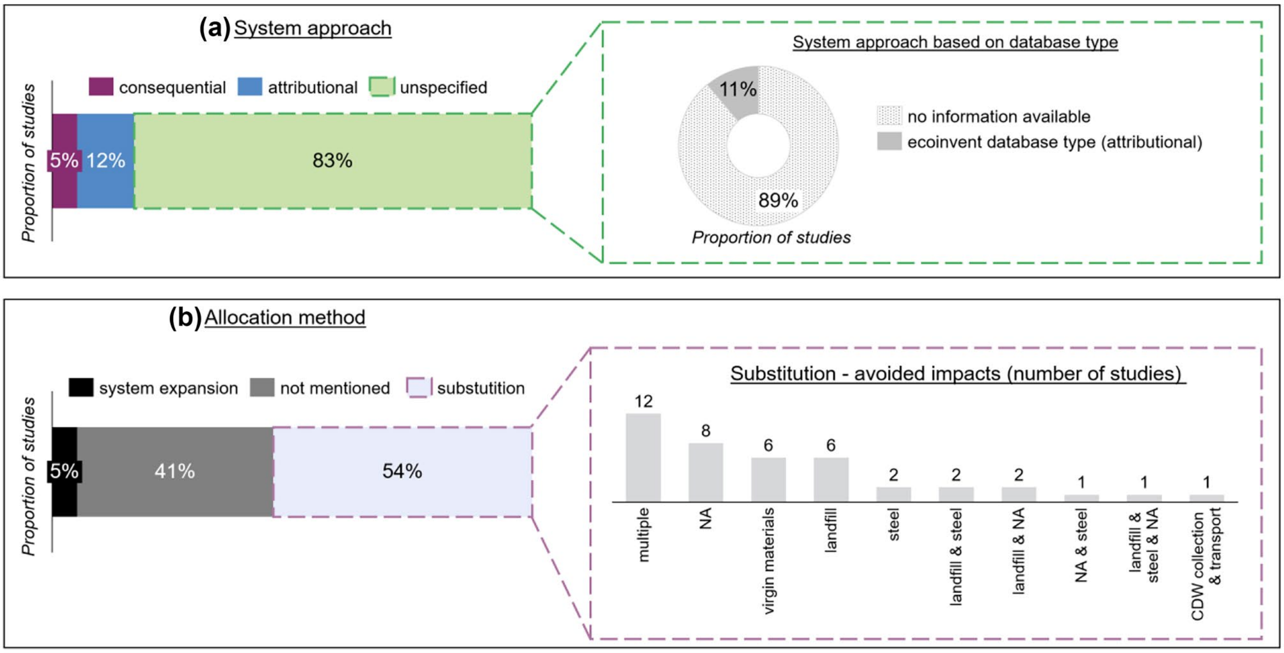


Fig. 7 Overview on (**a**) system approach followed: attributional and consequential and (**b**) allocation method followed: substitution or system expansion, and for the substitution main avoided impacts are summarized

impact allocation of end products, but also the database that is used in background systems is essential. None of the articles specifically mentioned the type of the ecoinvent database used for the consequential LCA, which can have a big impact on the result, as the background data creates the base of the CDW recycling model (electricity and diesel). This issue was also pointed out by Weidema (2017), where an error estimation on CLCA studies that were modeled using attributional background databases was presented, and the author concluded that, in average, for 401 impact categories assessed, 67% of the results have more than 10% difference, 22% of the results have more than 100% difference, and 16% of the results have more than 200% difference. The author emphasized the importance of using consequential background data for CLCA studies (Weidema 2017).

3.2.5 Allocation method

As CDW recycling has multiple end products and possible coproducts, the allocation and partitioning of environmental burdens between these products become a challenge. The allocation issue is also highlighted by ISO 14040/44 (2006) and stated that whenever possible, allocation should be avoided by (1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or (2) expanding the product system to include the additional functions related to the co-products, taking into account the requirements of the system boundary.

In this review, the articles were categorized into two main allocation methods followed: system expansion and substitution. We referred system expansion as expanding the system boundaries to include additional product systems to make two systems comparable. On the other hand, substitution was used as crediting for avoided impacts. Within the reviewed articles, 4 studies (Di Maria et al. 2018; Ding et al. 2016; Mah et al. 2018; Zhang et al. 2019b) followed the system expansion approach, where mainly the end products of compared systems were balanced through expanding to include NAs that were assumed to have the same quality as RAs. Majority of articles, 54%, applied the substitution approach, by including the avoided impact as environmental benefits in the system boundaries. As it was the most common approach, a detailed overview on the avoided impacts is presented in the following section.

Substitution (avoided impacts) Substitution is a widely used approach when it comes to assessing recycling systems. Based on the reviewed articles, no consistency on the avoided impact approaches in CDW recycling was observed. A detailed overview on avoided impacts including the substitution ratio, replaced material information, RA quality, and its inclusion in the LCA is presented in Table 2 (for the studies focusing on building and CDW recycling-RA

Table 2 Summary on the RA quality and its inclusion in the LCA, avoided impacts, and result interpretation (by means of GWP impact difference) for articles focusing on building and CDW recycling-RA production

Focus	Reference	RA quality mentioned	Avoided impacts	Result (based on GWP)	Inclusion of RA quality in LCA
Building	(Blengini 2009)	only one RA quality (mentioned as for low quality applications)	-steel (mix of virgin and steel scrap) -NA (no further information)	↓ Recycling < landfilling (37% less)	no
	(Hossain and Ng 2020)	fine & coarse RA	-metal: iron ore (1:1.4) -RA:NA (1:1) -wood waste: wood composite (1:1)	↓ Recycling < landfilling (60% less) Mainly due to avoided NA and iron ore	no
	(Hossain and Thomas Ng 2019)	unspecified	-energy: wood & timber (1:0.81) -metal: iron ore (1:1.4) -plastic: HDPE (1:0.81) -paper & cardboard: sulphate pulp (1:0.83) -copper scrap: copper (1:1) -glass cullet: glass (1:1) -concrete and ceramic tiles: NA (1:1) -hardwood: cement-bonded wood composite (1:1)	↓ Environmental savings due to avoided impacts (38% due to RA, 34% due to HDPE and 25% iron ore)	no
	(Lachat et al. 2021)	unspecified	none	↑ RA>NA -demolition and transport are the main contributors	no
	(Martínez et al. 2013)	unspecified	virgin materials (no further information)	↓ SD< TD (89% less)	no
	(Pantini and Rigamonti 2020)	LQ and HQ RA: HQ in concrete construction LQ in road construction	-liquid steel: liquid steel (1:1) -aluminium scraps: Al 99.7 (1:0.7) -particle board: plywood (1:0.6) -glass cullet: packaging glass (1:1) -RA HQ: NA (1:0.65) -RA LQ: natural sand (1:0.58)	↓ SD_HQ>SD_LQ>TD SD_HQ (48% less) SD_LW (7% less)	substitution ratio based on Borghi et al., 2018.
	(Pesta et al. 2020)	RA 0/4 mm, 4/8 mm and 8/16 mm	virgin materials (no further information)	↓ Reuse < recycle < landfill	no
	(Vitale et al. 2017)	fine & coarse RA	electricity-high voltage, sand, crushed limestone, steel, plastics, copper, glass	↓ Recycling has negative impacts, main savings by avoided steel	no
	(Welsh-Huggins et al. 2020)	RA to be used in concrete	none	↑ RAC>NAC due to increased cement input	no
CDW recycling – RA production	(Agrela et al. 2021)	4 different qualities SD (HQ) and TD source (3 qualities)	-RA: NA (1:1) – same for all 4 RA qualities	↓ Aggregate and road section level NA*>MRA-C>MRA-B>MRA-A>MRA-D (51-72% less) Road section with RA (99-100% less)	no
	(Blengini and Garbarino 2010)	3 different qualities	-landfill -steel (primary, converter steel) -RA:NA (1:1) – 3 different qualities	↓ Environmental savings through recycling Avoided impacts: landfill>steel>NA	yes, 3 different NA qualities according to RAs as avoided impacts
	(Borghi et al. 2018)	3 different qualities	-steel (primary) -NA (substitution coefficients were calculated considering the quality and the market demand for RAs)	↓ Recycling<landfilling (70% less) Stationary recycling causes less impacts than mobile	substitution ratio based on (Rigamonti et al. 2013)
	(Butera et al. 2015)	RA with 0.40 mm grain size	-NA (gravel pit extraction, its transportation to the road construction site and leaching)	↓ Recycling vs. landfilling (51% less) 30-40% reduction due to avoided transport, only 5-10% due to avoided NA	no information
	(Coelho and Brito 2013a, b, c, d)	fine & coarse RA	-ferrous metals: iron ore -aluminium, non-ferrous: bauxite ore -fine and coarse RA: limestone crushed -fine and coarse ceramic: river/sea sand -paper and cardboard: cellulose -plastic: oil derivatives -wood: wood particleboard & fiberboard	↓ Avoided impacts are 10 times higher than the impacts generated through recycling for GWP. Transportation accounts for 54% of total GWP	not included (same replaced material)
	(Cuenca-Moyano et al. 2019)	RFA of 0/2 mm and other fractions	-landfill incl. transport	↓ RA<NA (204% less)	no
	(Dahlbo et al. 2015)	fine & coarse RA	-NA (1:1) -iron (1:0.94) -aluminium (1:0.76) -avoided energy for wood and landfill	↓ Environmental benefits due to avoided impacts-avoided impacts through RA has the smallest and wood highest potential	no
	(Di Maria et al. 2018)	fine & coarse RA	-coarse RA: coarse NA (1:1) -fine RA: fine NA (1:1)	↓ SD is advantageous economic and environmental	yes, two different types of NA - coarse and fine
	(Estanqueiro et al. 2018)	unspecified	none	↑ Stationary RA>NA (58% more) mobile RA>NA (33% more)	no
	(Faleschini et al. 2016)	2 different qualities: LQ and HQ	-landfill	↓ LQ RA<NA (68% less) ↓ HQ RA<NA (59% less)	yes, different process data for LQ and HQ NA
	(Fořt and Černý 2020)	3 different qualities: as cement (CR), alkaline (AA) and RA	-RA: 0.83 -CR: 0.71 -AA: 0.65	↓ CR<AA<RA< landfill	substitution coefficients based on Borghi et al., 2018
	(Gan et al. 2016)	unspecified	-NA (no further information)	↓ RA<NA (29% less)	no
	(Ghanbari et al. 2017)	unspecified	none	↓ RA<NA (72% less)	no
	(Guignot et al. 2015)	RA to be used in concrete or road construction	none	↓ Alternative recycling < conventional recycling	no
	(Hossain et al. 2016)	fine (<5 mm) & coarse (5-20 mm)	-for the CDW only C&D waste collection and transport to fill sites -for waste glass avoided landfill	↓ fine RA<NA (64% less) coarse RA<NA (66% less)	no
	(Iodice et al. 2021)	3 types: HQ, MQ and LQ	-avoided transportation, land use and land use change, and virgin materials	↓ Best scenario with selective demolition enables environmental savings.	substitution coefficients based on Borghi et al., 2018
	(Jain et al. 2020)	coarse RA, recycled sand recycled soil	-coarse RA: avoided NA gravel, round (1:1) -recycled sand: avoided sand (1:1)	↓ Recycling < landfilling	two different avoided NA (gravel and sand)
	(Li et al. 2020)	fine & coarse RA	-landfill -NA	↓ Recycling has environmental benefits mainly due to avoided landfill	no
	(Liu et al. 2020)	RA and recycled powder	For all (1:1) replacement -steel, timber, plastic, aluminum, glass, coarse NA by masonry material waste, cement by mixed fragments	↓ Environmental savings by recycling, Avoided impacts: aluminum (46%), steel (36%) and RA (5%)	no

Table 2 (continued)

Focus	Reference	RA quality mentioned	Avoided impacts	Result (based on GWP)	Inclusion of RA quality in LCA
CDW recycling – RA production	(Lockrey et al. 2018)	unspecified	-landfill, transport, and virgin material (NA and steel)	🟦 ↓ Automatized crushing has environmental benefits	no
	(Mah et al. 2018)	two types: to be used in road and concrete production	-system expansion, 2 different NAs	🟨 → RA for concrete and NA for road construction has less impact than 50% RA for each application.	two different NAs for concrete and road construction are included
	(Martinez-Arguelles et al. 2019)	recycled concrete aggregate	-landfill	🟦 ↓ Concrete $_{\text{70\% NA \& 30\% RA mix}}$ < Concrete $_{\text{100\% NA}}$ (17% less)	no
	(Mercante et al. 2012)	RA: 4 different grain sizes	-paper & core board: sulphate pulp and core board (1:0.83) -RA: gravel (1:1) -metals: iron pig (1:1) -wood: wood chips softwood (1:1) -plastic: a mix of PE, PET, PVC, granulate (1:0.81)	🟦 ↓ Environmental savings through recycling. Wood and paper recycling has higher impacts than avoided impacts.	no
	(Mousavi et al. 2020)	unspecified	non-relevant	🟦 ↓ Recycling< Landfill	no
	(Park et al. 2019)	fine & coarse RA	none	🟥 ↑ RA (wet)> RA (dry) >NA – (106% and 166% more) RAC with 30% RA-70% NA > NAC (34% more)	mentioned but no difference in LCA
	(Penteado and Rosado 2016)	RA to be used in road construction	-virgin material production and transport	🟦 ↓ Recycling has environmental benefits mainly due to avoided impacts	no
	(Ram et al. 2020)	fine & coarse RA	-landfill and NA (1:1)	🟦 ↓ CDW recycling < landfill (219-156 % less)	no
	(Rosado et al. 2019)	RA for low and medium quality application fine RA (0.15-4.75 mm) coarse RA type A (4.75- -25 mm) coarse RA type B (0.1-50 mm)	-land-derived material: soil (1:1) -fine RA: sand and gravel (1:1) -coarse RA Type A: NA (4.75 to 20mm) (1:1) -coarse RA Type B: NA (0.1 to 50 mm) -wood chips : wood chips (1:1) -steel: primary (60%) and secondary (40%) steel (1:0.98) -plastic: different plastic types (1:0.81) -glass cullet: primary (55%) and secondary (45%) glass (1:0.82)	🟦 ↓ Recycling has environmental benefits, mainly due to avoided steel production. Avoided NA is not significant, but high-quality RA has higher environmental savings	different grain size of avoided NA for coarse and fine RA
	(Rosado et al. 2017)	mix RA to be used in road base and subbase	- inert landfill, wood chips, steel and land-derived material	🟦 ↓ RA<NA (mainly avoided landfill)	no
	(Simion et al. 2013)	unspecified	avoided steel/iron	🟦 ↓ Recycling 7 times lower than landfill	no
	(Vossberg et al. 2014)	unspecified	none	🟦 ↓ Recycling mobile and stationary (86% and 21%) less impact than landfill	no
	(Wang et al. 2018)	unspecified	no information	🟦 ↓ Recycling has environmental benefits by willingness to pay	no
	(Wu et al. 2015)	unspecified	-virgin materials, but no information	🟦 ↓ Material minimization < Recycling < Landfill	no
	(Yazdanbakhsh 2018)	RA to be used in road and concrete	none	🟨 → RA 75% road and 25% in concrete application is the best option. RA 100% concrete causes more impacts due to increased cement input.	no
	(Zhang et al. 2019b)	fine (0-4 mm) & coarse (4-22 mm) RA	system expansion, 2 types of NA	🟦 ↓ HAS mobile recycling <wet processing	yes, two different NA types
	(Zhang et al. 2018)	RA to be used in different purposes (road, structural…)	none	🟦 ↓ RA for concrete < RA for road construction. Environmental savings by avoided landfill	no
	(Zhang et al. 2020)	RA for road application	not mentioned	🟦 ↓ Recycling <. landfill (85% less)	no

For the articles, where no % values in GWP are given, the presented results in the articles do not allow as such comparison. If recycling has higher GWP impact than conventional option (NA, NAC production or landfill), then the results are 🟥 marked red. On the contrary, the results with environmental savings compared to conventional alternatives are 🟦 marked blue. If both environmental impacts and savings for different conditions are reported, then the results are 🟨 marked yellow (HQ: high quality, MQ: medium quality, LQ: low quality, SD: selective demolition, TD: traditional demolition (non-selective), HAS: Heating air classification system).

production) and Table 3 (for the studies focusing on concrete). Furthermore, the main outcomes based on GWP are also summarized in a way comparing the recycling option to the conventional one including % reduction on GWP, which is shown as delta (Δ), for the studies where the delta Δ was possible to be calculated as given in the Eq. (1).

$$\text{Delta}\Delta(\%) = \frac{\text{GWP}_{\text{recycling option}} - \text{GWP}_{\text{conventional system}}}{\text{GWP}_{\text{conventional system}}} \tag{1}$$

It is worth noting that Δ (%) values are included to have a better overview and not aiming to make a one-to-one comparison of the studies. As LCA includes various parameters and assumptions, a one-to-one comparison of Δ values can be misleading; thus, the values in Tables 2 and 3 requires careful interpretation. To ease the interpretation, the papers are presented for each focus group: building, CWD recycling—RA production, and concrete—road construction, based on the set FUs.

We observed that the avoided materials and substitution ratios differ from study to study. In addition, transparent reporting of the avoided materials and substitution rates is lacking, as only 13 studies reported the replaced materials and substitution coefficients. For example, virgin materials as avoided impacts were used 6 times without any further specification, which is a broad term and does not specify which materials are considered in the avoided impacts. From the results, it can be concluded that the studies that reported increased environmental impact (in this case GWP) compared to the conventional option generally did not include any avoided impacts. Some exceptions are reported in Table 2, such as Ghanbari et al. (2017), in which authors reported a great reduction in RA impacts compared to NA, but in this case, transport of CDW was not included and no information on by-products, which could end up in landfill, was given. When it comes to the different material groups, in the CDW recycling or RA production, very different approaches were observed. Some studies only included landfill as avoided impact, others all different material groups, and some authors included only NA. Rosado et al. (2019) highlighted the avoided steel impact as a crucial point for the avoided impacts of the CDW management system and mentioned that steel avoidance

Table 3 Summary on the RA qualities mentioned, avoided impacts, result interpretation (GWP), and additional cement input for articles focusing on concrete

Focus	Reference	RA quality mentioned	Avoided impacts	Result (based on GWP)	Additional cement
Concrete	(Ben Fraj and Idir 2017)	3 different from LQ to HQ:RA-1, RA-2, RA-3	none	↑ Aggregate - RA>NA 34% Concrete - RAC-1>NAC 15%, RAC-2>NAC 3%, RAC-3>NAC 2%	yes, 16% for LQ RA 3% for HQ RA
	(Braga et al. 2017)	coarse RA	no information	→ RA< NA (76%) RAC < NAC (except for C50/60 - RAC has higher impacts due to increased cement input)	yes
	(Colangelo et al. 2020)	RA with two different grain sizes	-NA (no further information)	↓ As the RA content in the concrete increases the environmental impact reduces	no
	(Colangelo et al. 2018)	unspecified	two types considering quality aspect -natural stone (for coarse RA) and -natural sand (for fine RA)	→ Concrete with 25% of RA has the lowest impact as 50% and 100% RAC require more cement and binder input	yes - 8% more
	(Ding et al. 2016)	unspecified	system expansion	↑ RAC>NAC (0.8% more)	yes - 7% more
	(Jiménez et al. 2015)	fine & coarse RA	none	RAC<NAC (2% less) - RAC with a lower MPa.	no
	(Kleijer et al. 2017)	recycled gravel	none	RAC<NAC (2% less, but only 28% RA input)	no
	(Knoeri et al. 2013)	no information	avoided landfill, transport, and iron scrap	RAC<NAC (70% less) Additional cement for RAC should not be above 10%	yes
	(Kurda et al. 2018)	fine & coarse RA	none	RAC<NAC (9% less)	no
	(López Gayarre et al. 2016)	RA to be used in concrete	none	↑ RA mobile> RA stationary >NA mobile plant transport impact is high	no
	(Marinković et al. 2010)	RA with 4/8, 8/16 and 16/31.5 mm	none	↑ RAC >NAC (4% more) NA transport distance>170km for RAC to have lower impact	yes - 5% more
	(Marinković et al. 2017)	RA with 4/8 and 8/16 mm	none	↑ RAC>NAC (12% more)	no
	(Martinez-Lage et al. 2020)	RA from concrete and mixed waste with 2 grain sizes: 4/12 mm & 12/24 mm	none	↑ RAC (mix)> RAC (concrete)> NAC 10.8 and 5.3% more impact	no – 6% less but more SP
	(Mistri et al. 2021)	unspecified	no	↑ RAC>NAC (14% more)	no
	(Napolano et al. 2016)	3 different type A, B, C (from HQ to LQ)	NA extraction and transport	↓ RAC<NAC transport distance is important, also the avoided impacts	yes (6-16% more)
	(Pavlu et al. 2019)	coarse RA, 2 different grain sizes (4/8 & 8/16 mm)	no	↓ RAC<NAC - RAC-coarse -22% less - RAC-fine -26% less - RAC-cement replaced -28% less	no
	(Pradhan et al. 2019)	fine & coarse RA	not mentioned	↓ RAC<NAC	no (less cement)
	(Sabau et al. 2021)	no	CDW recycling - avoided landfill	↓ RAC>NAC due to more superplasticizer	no
	(Schepper et al. 2014)	coarse RA	avoided materials- but no further information	↓ Completely recyclable concrete< Traditional concrete< landfill	no, less cement, but added SP
	(Serres et al. 2016)	recycled sand & recycled coarse gravel	no information	↓ RAC fine&coarse - 25% less than NAC RAC coarse - 15% less than NAC	no, but added SP
	(Suárez Silgado et al. 2018)	"Type 2" mixed aggregates according to German regulation	avoided steel for RA avoided cement for RGC	↓ RAC 18% less, RGC 113% less than NAC	no
	(Tošić et al. 2015)	unspecified	no	↑ RAC>NAC (4% more)	yes, 3% more
	(Turk et al. 2015)	unspecified	-landfill, transport to landfill and metal	↓ RAC<NAC	no
	(Vega A et al. 2020)	coarse RA to be used in road construction	none	→ Road with lowest RA- lowest impact, as thicker road section is required for higher RA.	no
	(Visintin et al. 2020)	unspecified	no information	→ RA<NA if transport is low otherwise no	yes
	(Xia et al. 2020)	unspecified	none	↓ RAC<NAC (15% less)	no
	(Xiao et al. 2018)	coarse RA	no information	↓ RAC<NAC (8% less)	yes, 2% more
	(Yazdanbakhsh et al. 2018)	2 qualities: HQ and LQ	-landfill	↓ RAC<NAC (0.3% less)	yes, 8% more and 0.5% more SP
	(Yazdanbakhsh and Lagouin 2019)	unspecified	-landfill and transportation	↓ RAC with landfill avoided 27% less, otherwise only 1% less	yes, 8% more and 0.5% more SP
	(Zhao et al. 2020)	4 different grains sizes and application areas	-avoided RCA other fractions (6.3/14 mm and 14/20 mm) (by products)	↓ RAC<NAC (0.9% less)	no

For the articles, where no % values in GWP are given, the presented results in the articles do not allow as such comparison. If RAC has higher GWP impact than NAC, then the results are marked red. On the contrary, the results with environmental savings compared to conventional alternatives are marked blue. If both environmental impacts and savings for different conditions are reported, then the results are marked yellow (HQ: high quality, LQ: low quality, SP: Superplasticizers).

causes 77% of GWP impact reduction. A similar statement was also done by Pantini and Rigamonti (2020), where the authors compared selective and non-selective demolition and found out that 83% of material recovery can be achieved through steel recycling. In addition, Vitale et al. (2017) highlighted that even though steel only accounts for 3% of the total CDW mass, it provides the largest contributions to avoided impacts with an 89% reduction in GWP. Another issue that was observed through this review regarding steel is the type of replaced steel and the replacement ratio. Vitale et al. (2017) also remarked on the importance of the type of steel as avoided impact and compared three different avoided steel types: a mix of primary and secondary steel, only secondary steel, and only primary steel. The results showed that using only secondary steel as avoided impact causes environmental impacts rather than benefits, contrary to considering only primary steel where environmental benefits are huge.

The biggest difference in the results was observed for the articles focusing on concrete. It was observed that the studies that did not include any avoided impacts for RAC generally end up with a higher GWP compared to NAC (Ben Fraj and Idir 2017; Marinković et al. 2010; Martinez-Lage et al. 2020; Mistri et al. 2021). As the focus is on concrete, most of the studies did not mention RA production in detail (such as byproducts and allocation). In addition, 40% of the studies reported extra cement input for RAC compared to NAC, remaining 60% did not consider an increased cement input for RAC. As cement production is the main contributor to the environmental impacts in concrete production, the inclusion of extra cement can have a big impact on the results. This issue was also mentioned by Visintin et al. (2020), where the authors concluded that for a concrete strength capacity over 45 MPa, RAC causes higher impacts due to the increased cement requirement compared to NAC.

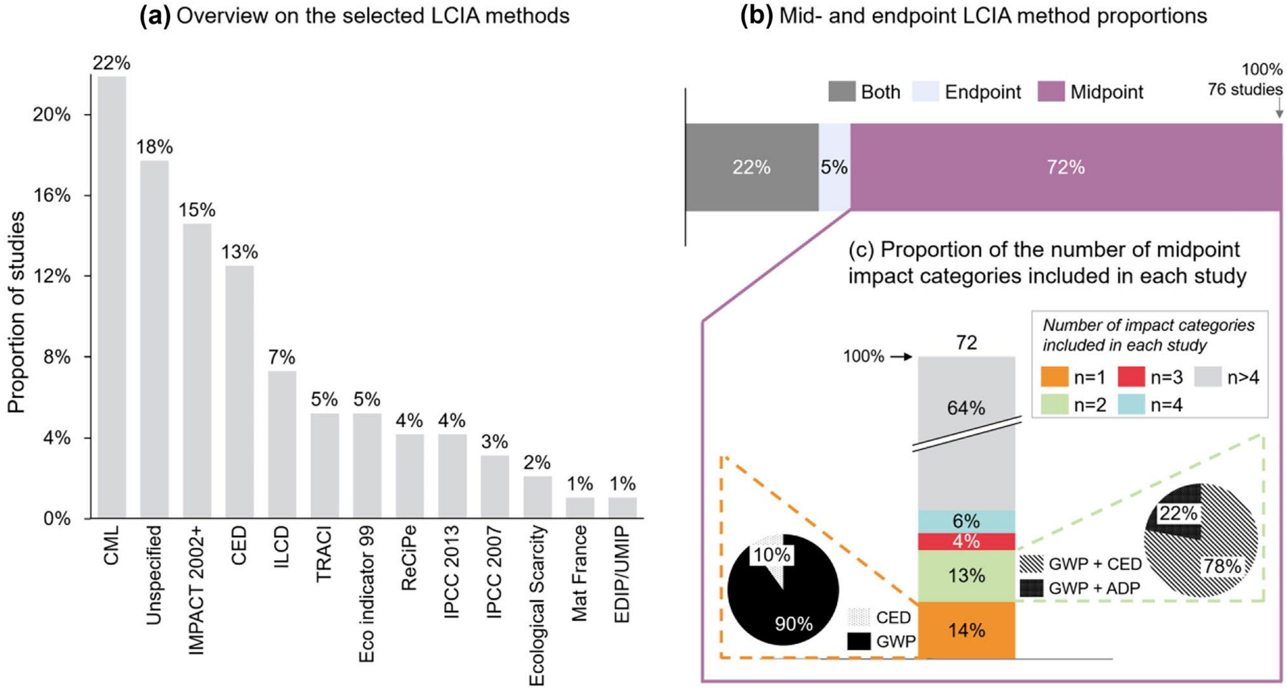


Fig. 8 An overview on (a) LCIA methods and (b) the number of impact categories that are included in reviewed articles

Another important topic is RA quality, as through recycling different qualities of RA with different application areas are produced. Even though, 67% of the studies mentioned different RA qualities, either as quality levels or different particle sizes and application areas, only 12 studies included the RA quality aspect in the LCA, by two ways:

1. Considering different NA qualities that correspond to different qualities of RA produced in the avoided impacts or system expansion approach.
2. Replacement coefficient introduced by Rigamonti et al. (2013) based on Eq. (2).

$$R = Q_1 * Q_2 * M \tag{2}$$

where Q_1 coefficient considers the purity of RA, where clean composition will have a value of 1, and if impurities such as soil, wood, plastics exist, then the value will be less than 1. Q_2 coefficient considers the technical characteristics of RAs compared to the placed material considering the application areas. If the same application is possible then, a value of 1 will be given. M refers to the market coefficient, which is defined as the ratio between the amount of sold and produced RAs, $M = 1$ indicates that the produced RAs are totally sold.

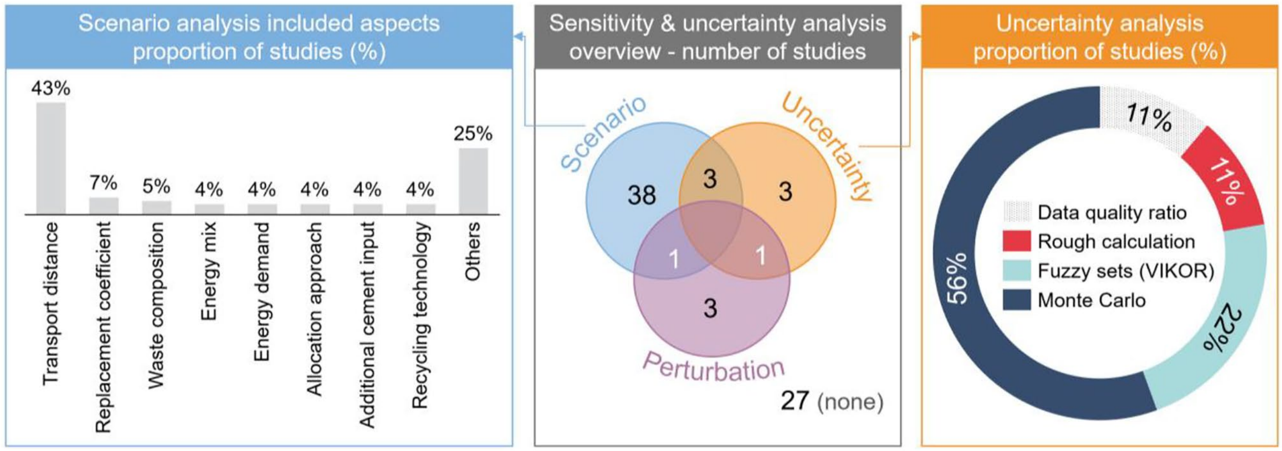


Fig. 9 Sensitivity and uncertainty assessment overview

Table 4 Summary of recommendations for the future LCA studies on CDW recycling

Functional unit:

- Include both input and output in the FU for recycling systems, specify the input waste composition and end product qualities & application areas in the FU
- If relevant, include multiple functional units. For instance, for concrete two levels of FU: (1) RA and (2) RAC to increase the transparency
- Avoid using unitary FUs and differentiate the FU with reference flow

System approach:

- Explicitly mention the system approach (attributional vs. consequential) followed, providing reason for the selection
- Use the database in align with the selected system approach and state it explicitly: APOS, cut-off, consequential

***Avoided impacts/system expansion*:**

- Consider the quality aspect and market demand of avoided impacts. A good example is the replacement coefficient introduced by (Rigamonti et al. 2013) where both the quality (technical and purity) and market demand are considered
- Do not use the same avoided impact for two different RA qualities
- Document the data used transparently and completely, both for RA/RAC and avoided impacts

Sensitivity & uncertainty analysis:

- Conduct both sensitivity analysis to identify the effect of a model input on the result and uncertainty analysis to quantify the overall uncertainty of the results
- Including replacement coefficient, market demand, and transport distances in the sensitivity analysis is useful

We found the replacement coefficient introduced by Rigamonti et al. (2013) as a relevant and comprehensive approach, in which both the quality and market demand are considered. However, as the data collection can be challenging, and the data sources, whether the data is based on assumptions, industry data, or literature value, should be clearly stated and included in the sensitivity analysis. In addition, further research on differentiation of two quality coefficients based on purity and technical characteristics, should be further investigated to clarify whether any overlapping occurs, which can lead double counting.

Concerning LCA for the building sector, EN 15804 (CEN 2021) is relevant for the product level and EN 15978 (CEN 2011) for the building level. Both standards include life cycle phases from Module A to C (production to EOL) and additionally Module D. Modules A–C follow the cut-off approach (100:0), and Module D considers the potential benefits of reusable or recycled products and should be reported separately. Within the studies reviewed, only two studies (Kurda et al. 2018; Serres et al. 2016) addressed EN 15804; however, none of these studies mentioned Module D or considered avoided impacts. The consideration of Module D in EN 15804/15978 is important in the CE context, and the quality of recycled material is included in the Module D calculation. However, Module D calculation is criticized for not properly distinguishing between open-loop and closed-loop recycling, which is an issue that requires further improvement (van Gulck et al. 2022).

Inadequate description of substitution modeling in waste management systems was also highlighted by Vadenbo et al. (2017), where the authors stated that modeling of avoided primary materials often suffers from being performed in an unsystematic and nontransparent manner. A framework that reflects different situations by introducing a flexible approach, where displacement rates based on either technical or economic information, was suggested. However, the authors also recommended future studies to undertake the link between technical functionality and product displacement in market-based approaches (Vadenbo et al. 2017).

3.2.6 Life cycle impact assessment method

LCIA is the third stage of LCA, according to ISO 14044 (2006), where elementary flows from LCI will be transposed to the impact categories and the potential contribution of each elementary flow is addressed to the environmental impacts. There are various LCIA methods available, and within each method different LCIA categories exist.

18% of the studies did not indicate the LCIA method that was selected. Majority of studies used the CML method followed by IMPACT 2002 + and CED (see Fig. 8). In terms of mid- and endpoint impact methods, midpoint LCIA methods applied in 72% of the studies followed by both mid- and endpoint methods. Within the midpoint assessment, it is seen that 14% of the studies included only one impact category, mainly as GWP, except for one paper where CED was used. Similarly, the number of studies focusing only on two impact categories is also relatively high, 13%. As different impact categories can give different results, it is important to comment on different impact categories and critically interpret the results. A study done by Chen et al. (2021b) highlighted the importance of LCIA method selection and drew attention to the uncertainties that can occur due to the impact method, which are often ignored by LCA practitioners. The LCA practitioners should be aware of the potential uncertainties of the impact method, be able to justify the selection of the impact categories, and interpret the results critically.

3.2.7 Sensitivity and uncertainty analyses

Data quality analysis is included within ISO 14044 (2006) to better understand the significance, uncertainty, and sensitivity of the LCIA results. In addition, in ISO 14044 (2006), it is stated that uncertainty and data quality analysis should supplement results for completeness, sensitivity, and consistency check of the study.

Through this review, we identified that only 9% of the selected articles assessed the uncertainty of the LCA study, mainly through Monte Carlo simulation and fuzzy sets (see Fig. 9). Majority of articles conducted a scenario analysis, which is mainly a one-factor-at-a-time method to evaluate the robustness of results and spot the most sensitive parameters that could affect the results. Within the reviewed studies, the main scenario analysis was performed on transport distances. For instance, Blengini and Garbarino (2010) evaluated the delivery distance RA compared to NA delivery distance, which was 70% in the base scenario, and concluded that the transport distance ratio of RA to NA should be under 300% for net environmental gain to be achieved through recycling. Some other authors focused on NA distance (Ben Fraj and Idir 2017; Guignot et al. 2015; Ram et al. 2020) to assess the minimum transport distance of NA, where recycling will still have environmental benefits. In addition, the transport distance between the demolition site and the CDW recycling plant was also included in the sensitivity analysis. For example, Pantini and Rigamonti (2020) stated that a radius of 30 km is a good margin to ensure the net environmental benefits for selective demolition. In addition to transport distance, the vehicle type selected in the LCA was also included in the sensitivity analysis by Cuenca-Moyano et al. (2019) and Visintin et al. (2020), where Visintin et al. (2020) found out that using EURO 5 lorry instead of fleet average can save from 0.4% up to 17% depending on the impact category. Faleschini et al. (2016) included the use of PV as the energy source in the scenario analysis, in addition to transport distance in the sensitivity analysis. This is a good option to compensate for the increased transport distance, which is an interesting and useful assessment. Similarly, Coelho and Brito (2013d) included also renewable energy in the sensitivity analysis on transport, where in addition to diesel, biofuel, and electricity were modeled as energy sources for the transportation process, and it was observed that having electricity as the energy source for transportation can save around 30% of GWP compared to diesel. In addition to transport, other aspects were also assessed; for instance, Borghi et al. (2018) performed a comprehensive sensitivity analysis, including avoided product replacement ratio, market coefficient of RA, CDW recycling plant type, and a best scenario where all aspects are set to the best value to assess the maximum environmental potential of the suggested CDW management system. A study done by Jiménez et al. (2015) included the use of different kinds of cement in RAC production, which was not considered by other authors focusing on concrete production. Lachat et al. (2021) included 3 different allocation approaches (0:100, 100:0, 50:50) in sensitivity analysis to allocate the total environmental impacts between a demolished building and RA produced. The authors concluded that following the 100:0 approach hinders the use of RA compared with NA because of the enormous difference in environmental impacts. Using the 50:50 approach lowers the impact of RA but is still not beneficial compared with NA. The 0:100 approach was stated to be the most effective in promoting the use of RA compared to NA, as it resulted in a lower value for RA than NA in 4 of the 8 impact categories. It is worth noting that different results were reported depending on the impact category, for example, RA had lower impacts than NA on abiotic depletion potential for all allocation approaches. Another interesting example, which was previously mentioned in Sect. 3.2.1 Functional unit, was conducted by Marinković et al. (2017), where serviceability and durability of concrete were also included in the FU to evaluate the sensitivity of the selected FU on different concrete mixes. Even though the results did not reveal a big difference, the approach is interesting for the studies focusing on LCA of RAC.

4 Conclusions and future prospect

Through this systematic literature review, we identified some methodological issues on LCA studies focusing on CDW recycling that are not aligned with ISO 14044 (2006). One main issue is the lack of transparent reporting, as we observed that more than 18% of studies did not specify the software, database, or LCIA method used. Similarly, in terms of FU, a tendency to select unitary FUs was present, where relevant information such as waste composition or RA quality was not mentioned. We also took a closer into the avoided impacts, their substitution ratio, and inclusion of the RA quality aspect in LCA and remarked that the RA quality aspect was rarely included in the LCA. Within the CE, in order to differentiate the downcycling and recycling, recycled material quality plays an essential role. Thus, we strongly recommend future LCA practitioners to give special attention on the quality aspect. In addition, as data availability is a known challenge, especially in CDW recycling, sensitivity and uncertainty analyses should be included. The recommendations are summarized in Table 4, based on the review results to give a direction for future LCA studies.

Within this review, some malpractices including the principle LCA elements, such as misunderstanding and wrong definition of FU, were observed. Proper application of LCA methodology is essential for reliable and consistent LCA results. Thus, the LCA practitioners should follow the principal of LCA methodology and peer-reviewers should carefully check the LCA studies to ensure the proper implementation. Within this review, some important LCA aspects are highlighted, and recommendations are provided in Table 4. For LCA studies in CDW recycling, we observed that, there is a need for a standardized and well-defined avoided impact framework to improve the quality and reliability of future LCA studies.

Even though this review provides a comprehensive and detailed overview of LCA studies focusing on CDW recycling, it has some limitations. Only literature in English was considered in the selection process, which may lead to the omission of relevant literature in other languages. Similarly, only articles from peer-reviewed journals were considered, while gray literature that may be relevant to this study was excluded.

Appendix

LCSA aspects, environmental, economic, and social, studied in each article are presented in Table 5. Recycling data that was presented in reviewed papers are summarized in Table 6; only the studies that documented the recycling data are included. In Fig. 10, keyword co-occurrence and journal analyses based on selected articles are presented.

Table 5 Overview on the sustainability aspects assessed in selected articles

LCA (n = 76)

(Agrela et al. 2021)
(Ben Fraj and Idir 2017)
(Blengini 2009)
(Blengini and Garbarino 2010)
(Borghi et al. 2018)
(Butera et al. 2015)
(Colangelo et al. 2020)
(Colangelo et al. 2018)
(Cuenca-Moyano et al. 2019)
(Dahlbo et al. 2015)
(Ding et al. 2016)
(Estanqueiro et al. 2018)
(Faleschini et al. 2016)
(Fořt and Černý 2020)
(Guignot et al. 2015)
(Hossain et al. 2016)
(Hossain and Thomas Ng 2019)
(Hossain and Ng 2020)
(Jain et al. 2020)
(Jiménez et al. 2015)
(Kleijer et al. 2017)
(Knoeri et al. 2013)
(Kurda et al. 2018)
(Lachat et al. 2021)
(Li et al. 2020)
(Lockrey et al. 2018)
(López Gayarre et al. 2016)
(Marinković et al. 2010)
(Marinković et al. 2017)
(Martínez et al. 2013)
(Martinez-Arguelles et al. 2019)
(Mercante et al. 2012)
(Mistri et al. 2021)
(Mousavi et al. 2020)
(Napolano et al. 2016)
(Pantini and Rigamonti 2020)
(Park et al. 2019)
(Pavlu et al. 2019)
(Penteado and Rosado 2016)
(Pesta et al. 2020)
(Pradhan et al. 2019)
(Ram et al. 2020)
(Rosado et al. 2019)
(Rosado et al. 2017)
(Sabau et al. 2021)
(Schepper et al. 2014)
(Serres et al. 2016)
(Simion et al. 2013)
(Turk et al. 2015)
(Vega A et al. 2020)
(Visintin et al. 2020)
(Vitale et al. 2017)
(Vossberg et al. 2014)
(Wang et al. 2018)
(Wu et al. 2015)
(Xia et al. 2020)
(Xiao et al. 2018)
(Yazdanbakhsh 2018)
(Yazdanbakhsh et al. 2018)
(Yazdanbakhsh and Lagouin 2019)
(Zhao et al. 2020)

LCC (n = 15)

(Braga et al. 2017)
(Coelho and Brito 2013a, b, c, d)
(Di Maria et al. 2018)
(Gan et al. 2016)
(Ghanbari et al. 2017)
(Liu et al. 2020)
(Mah et al. 2018)
(Martinez-Lage et al. 2020)
(Suárez Silgado et al. 2018)
(Welsh-Huggins et al. 2020)
(Tošić et al. 2015)
(Zhang et al. 2019b)
(Zhang et al. 2018)
(Zhang et al. 2020)

S-LCA (n = 1)

(Iodice et al. 2021)

Table 6 Summary on the available recycling data that was given in the reviewed studies. The given data is summarized in four main groups, considering different plant types: stationary (S) or mobile (M), and the processing technique: wet, wet and dry (combined), and conventional

Processing type	Reference	Electricity (kwh)	Diesel	Water (l)	Data given per ton of	End product (%)
Wet _S	(Ben Fraj and Idir 2017)	1.5	2.75 MJ	67.7	RA	Unspecified
	(Jain et al. 2020)	6–10	0.4–1 L	20	Not mentioned	50% coarse RA 25% sand 25% soil
	(Ram et al. 2020)	0.812	1.35 L	6.33	RA	72.5% RA (coarse and fine)
	(Zhang et al. 2019a, b)	4	0.27 MJ	6.7	CDW	52.9% RCA 44.5% SS 2.6% rest
Wet and dry (combined)_S	(Di Maria et al., 2018)	24.4	0.9 MJ	–	CDW	73% coarse RA 18% fine RA 9% rest
Conventional_M	(Blengini and Garbarino 2010)	–	0.69 L	–	CDW	99.7% LQ 0.3% Steel
	(Borghi et al. 2018)	–	0.64 L	1.56	CDW	39.8% LQ 59.3% MQ
	(Marinković et al. 2010)	–	18.18 MJ	–	RA	60% RA 40% rest
	(Tošić et al. 2015)	–	49.01 MJ	–	RA	Unspecified
	(Turk et al. 2015)	–	0.3 L	–	RA	Unspecified
	(Vossberg et al. 2014)	–	0.5 kg	–	CDW	Unspecified
Conventional_S	(Di Maria et al., 2018)	6.11	0.9 MJ		CDW	96% fine RA 4% rest

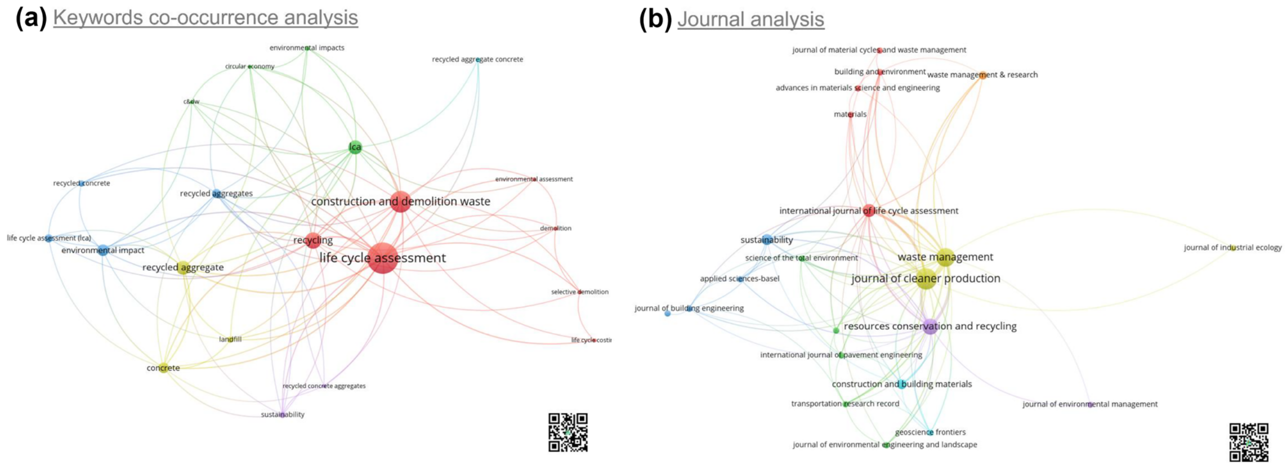


Fig. 10 Overview on (**a**) keywords co-occurrence analysis using author keywords option (access through this link (https://tinyurl.com/2285d7qy)) and (**b**) journal analysis (access through this link https://tinyurl.com/2cmjdvef), using VOSviewer. Different colors indicate different clusters, and the size of circles indicates the frequency

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Declarations

Conflict of interest The authors declare no competing interests.

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