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Review

A meta-analysis of environmental impacts of building reuse and recycling

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ABSTRACT

Significant efforts have been made to assess the environmental impacts of building reuse and recycling, involving various life cycle assessment (LCA) methodologies and different types of buildings and materials. Consequently, the conclusions regarding the environmental impacts of building reuse and recycling can vary across studies. This study aims to clarify the environmental benefits of reuse compared to recycling scenarios, as well as the advantages of recycling compared to landfilling scenarios. Separate meta-analyses were conducted based on both partial and full harmonization methods. The partial harmonization aligned the functional unit, system boundary, impact allocation methods, and upstream processes of the shortlisted studies, while the full harmonization method further made inventory data and the life cycle impact assessment method consistent. The results indicate that after the partial harmonization of LCA studies, the environmental impact from reuse scenarios averages 58.2 % of those from recycling scenarios, while the impact from recycling scenarios averages 61.1 % of those from landfilling scenarios. After fully harmonizing LCA studies, these ratios increase to 62.9 % and 73.5 %, respectively. Furthermore, the results reveal that the environmental impacts of reusing mass timber and Design for Disassembly modular buildings account for only about 20 %–50 % of those associated with recycling. This paper represents the first effort to produce generalizable findings regarding the environmental impacts of building reusing and recycling. It provides solid evidence that priority should be given to reuse before recycling. Recommendations are also provided for promoting building reuse and recycling.

1. Introduction

The adoption of a circular economy becomes an important strategy for tackling two major environmental challenges in the construction industry in terms of excessive resource consumption and significant construction and demolition waste (CDW) generation (Oluleye et al., 2022; Tanthanawiwat et al., 2024). Recycling has been a conventional strategy for dealing with CDW sustainably, contributing to a reduction in environmental impact compared to landfilling (Jain et al., 2020; Llatas et al., 2022; Tanthanawiwat et al., 2024). However, recycling often involves complex processes that require preliminary activities for sorting large amounts of construction waste from demolition (Bao et al., 2020; Ma et al., 2020; Vefago and Avellaneda, 2013), and is accompanied by carbon emissions arising from certain recycling and transportation processes (Wang et al., 2022). A certain recycling rate (i.e., 50 %) should be achieved to obtain environmental benefits that surpass such environmental impacts (Wu et al., 2021). Nevertheless, the recycling rates of CDW vary across materials, which are affected by material properties, building designs, sorting and collection techniques, and so on (Galán et al., 2019; Ma et al., 2020). Consequently, the environmental benefits of recycling over landfilling can vary across materials.

(Direct) reuse is an effective way to reduce the demand for virgin resources and the environmental impacts of CDW (Selvaraj and Chan, 2024; Yuan and Shen, 2011). It has been argued that the focus of a circular economy should shift from recycling toward waste prevention and component reuse strategies (Joensuu et al., 2020; Yang et al., 2022). Reuse is prioritized over recycling in the context of waste management and the circular economy because it creates greater value retention (Kröhnert et al., 2022; Yang et al., 2022). For instance, Eberhardt et al. (2019) found that reusing Design for Disassembly (DfD) concrete components can result in approximately 20 %–60 % environmental impact savings compared to non-reuse scenarios (i.e., recycling and landfilling).

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Similarly, the reuse of DfD modular units leads to a 287 kg CO2-eq lower impact on global warming potential (GWP) than recycling and landfilling (Jayawardana et al., 2023). Direct reuse of the foundation, wooden ceiling elements, and load-bearing steel structure for a subsequent second building has been found to reduce greenhouse gas (GHG) emissions by 14 % (Kröhnert et al., 2022). Compared to recycling, the reuse of building components has been shown to offset GHG emissions by 88 % while also providing benefits across several other environmental indicators (Minunno et al., 2020). While these studies have reached a consensus on the environmental benefits of reuse over recycling, such benefits may highly depend on the reusability of building components. In other words, better reusability owing to DfD may result in more building components being directly reused and less waste generated (Yang et al., 2024), thereby mitigating the need for processing recycling and/or landfilling and avoiding corresponding environmental consequences.

While a reuse strategy is generally considered more advantageous than a recycling one, the implementation of the reuse strategy may encounter challenges in various regions. In some developed countries, building reuse practices have been supported by relevant building regulations and codes and advanced digital tracking technologies (Condotta and Zatta, 2021; Honic et al., 2021). Despite these advantages, the uncertainty in the financial benefits of reuse may discourage stakeholders from engaging in building reuse practices (Guerra and Leite, 2021; Osei-Tutu et al., 2023). On the other hand, developing countries often struggle with limited expertise in deconstruction and insufficient material tracking technologies (Bello et al., 2024; Bilal et al., 2020). As a result, building reuse practices are rare in developing countries, with reuse rates frequently stagnating at 10 % or even lower (Wang et al., 2024).

It is commonly claimed that the environmental benefits of reuse outperform those of recycling, while the environmental benefits of recycling outperform those of landfilling. This claim is based on a wide range of construction materials, design methods, and life cycle assessment (LCA) methodologies; however, making a general assertion is not advisable (Peng et al., 2022). On one hand, many prior LCA studies have examined reusing or recycling a wide range of building materials (e.g., concrete, steel, or wood) or construction methods (e.g., conventional or modular construction). However, a single study alone cannot provide a comprehensive view of how the environmental benefits of reuse and recycling are quantified and differentiated across various materials or design methods. On the other hand, many studies have assessed different scenarios of reuse, recycling, and landfilling, with the adoption of disparate scopes, boundary systems, life cycle inventories, and life cycle impact assessment (LCIA) methods. These divergent factors hinder the direct comparison of environmental impacts (Peng et al., 2022) of reuse and recycling, making it difficult to produce generalized or consistent findings on the extent to which reuse and recycling benefit the environment. Additionally, most narrative literature reviews on the environmental impacts of reusing building components and recycling materials overlooked differences in LCIA methods and the inventory data used (e.g., Ghisellini et al., 2018; Mesa et al., 2021; Purchase et al., 2022).

To address the limitations of narrative literature reviews, a meta-analysis can help ascertain the environmental impacts of reuse and recycling across multiple studies. For example, Minunno et al. (2021) conducted a meta-analysis that synthesized LCA outcomes, concluding that timber structures produce 68 % lower carbon emissions than concrete structures. However, limited efforts have been made to test the robustness of these meta-analysis results by considering the influence of LCA methods used in individual studies. Without harmonizing LCA methodologies, the conclusions may lack reliability, precision, and generalizability regarding true environmental impacts. To reduce heterogenies among individual studies, Peng et al. (2022) harmonized the functional unit, allocation approach, system boundary, and characterization factors to compare the life cycle environmental impacts of remanufactured products with their new counterparts. They further emphasized the need for sensitivity and uncertainty analyses to enhance the robustness of the meta-analysis of LCA studies.

This study aims to offer generalized meta-analyses of the environmental benefits of reuse compared to recycling, as well as the benefits of recycling compared to landfilling. First, the study uses the partial harmonization method to align the functional unit, system boundary, impact allocation method, and upstream processes of the selected LCA studies. This approach creates a more uniform framework for the LCA, facilitating a fair comparison between different end-of-life (EoL) strategies (Peng et al., 2022). Second, the study employs the full harmonization method, which further utilizes consistent inventory data and LCIA methods to re-assess the environmental impacts of individual LCA studies. The purpose of adopting these two LCA harmonization methods is not to determine which one can yield more accurate results. Instead, it seeks to enhance understanding of the influence of different levels of LCA harmonization on meta-analysis outcomes. Accordingly, separate meta-analyses are conducted to synthesize the results of individual LCA studies based on both the partial and full harmonization methods. This allows the researchers to quantify, synthesize, and harmonize these studies (Deeney et al., 2023), leading to generalized conclusions rather than just a generic summary of multiple studies (Peng et al., 2022). Building on the results of the meta-analysis, this study further examines the influence of building designs and materials on the environmental benefits of reuse and recycling.

To the best of the authors' knowledge, this is the first attempt to conduct a meta-analysis of LCA studies to generalize the environmental benefits of reusing and recycling building products based on harmonized LCA methods. This paper contributes to the existing body of knowledge in two key ways. First, it extensively harmonizes the LCA methodologies used in the individual studies. This harmonization process enables a meta-analysis to provide valuable insights into the generalized environmental benefits of building reuse and recycling. By doing so, the paper explores how different LCA methodologies affect the meta-analysis outcomes. Second, the meta-analysis clarifies which factors, such as building designs and materials, can significantly influence the environmental benefits of reuse and recycling. Finally, the findings provide practical recommendations for policymakers and industry practitioners on improving building design and recycling technologies to enhance these benefits.

2. Methodology

The methodological workflow of the present study comprises seven steps, as illustrated in Fig. 1. Firstly, a comprehensive literature search was conducted across multiple scholarly databases to retrieve relevant publications. Secondly, eligible papers were screened based on predefined inclusion criteria. Thirdly, relevant LCA data were extracted from these selected papers. Following that, the partial harmonization method was used to address the methodological heterogeneity. This method aligned the functional units, allocation methods, system boundaries, and upstream processes among the shortlisted studies. Building on the partial harmonization method, the full harmonization method was used to recalculate the environmental impacts using the consistent LCIA method and database, and was supplemented with uncertainty analysis. Subsequently, with the harmonized LCA results, a meta-analysis was performed to compare the environmental performance of different scenarios and synthesize results from the individual studies. After that, a sensitivity analysis was conducted to identify critical factors that might influence the outputs. Finally, a validity test was performed to examine how the harmonized method influences the robustness of the meta-analysis results.

2.1. Literature search

The selection of studies followed the Preferred Reporting Items for

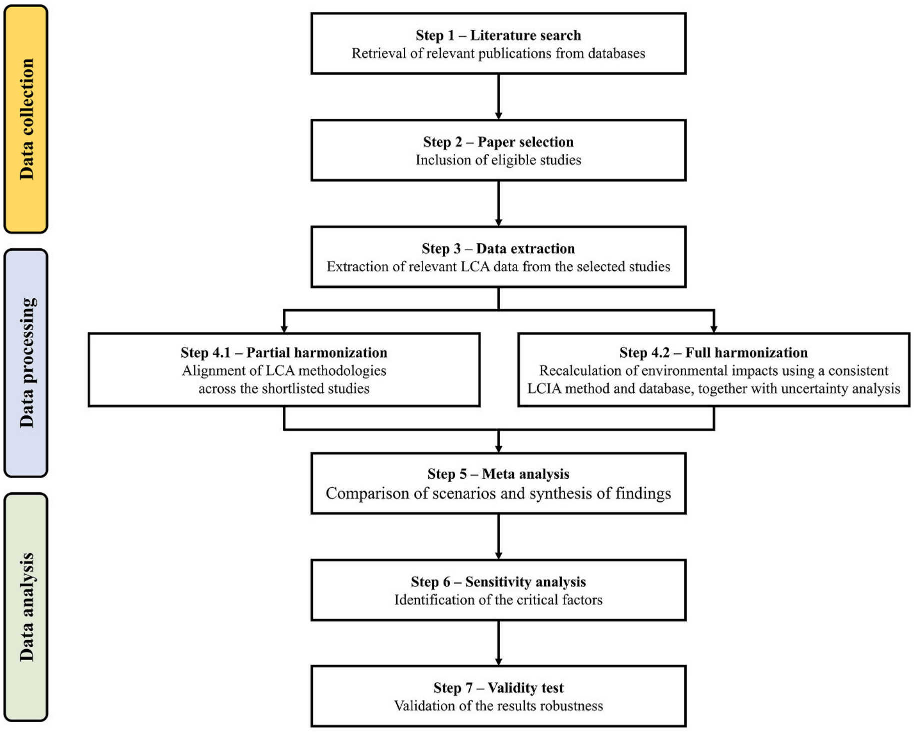


Fig. 1. Methodological workflow diagram.

Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a structured approach to conducting systematic reviews and meta-analyses. In accordance with the PRISMA framework (Tricco et al., 2018), we performed a comprehensive literature search through Web of Science and Scopus. The search aimed to collect studies that had compared environmental impacts between reuse (a combination of reuse, recycling, and landfilling) and recycling scenarios (a combination of recycling and landfilling), or between recycling and landfilling scenarios. As shown in Appendix Table A1, the search keywords were derived from previous review papers, including "building", "circular economy", "circular", "life cycle assessment", "reuse", "recycling", "environment", "End-of-Life", "scenario", "compar*", and other similar keywords (Chen et al., 2022; Peng et al., 2022). These keywords were then combined using Boolean logic operators and advanced search modifiers to refine the query. The specified query strings for searches in Scopus and Web of Science are shown in Appendix Table A2.

The search query was designed based on the research objectives. Firstly, to ensure sector specificity, terms such as "building" were used to target the building sector and exclude unrelated fields. Secondly, this study focues on the EoL stage of buildings, incorporating keywords like "End-of-Life" and "EoL" to capture research relevant to this phase (Chen et al., 2022). Thirdly, to compare reuse- and recycling-based strategies, and recycling versus landfilling strategies, nested Boolean logic was employed to retrieve relevant articles. Moreover, to better understand the environmental impacts and benefits of various treatment strategies, terms such as "environment" and "life cycle assessment" were included to ensure that the selected studies had conducted LCAs. Lastly, following the recommendations of Peng et al. (2022), keywords like "scenario" and "compar*" were used to identify studies involving scenario comparisons. The search was limited to English-language publications from 2004 to 2024, as a 20-year timeframe is commonly used in review studies to ensure literature timeliness (Bao et al., 2024; Lueddeckens et al., 2020). The search focused on journal articles and conference papers to ensure the selection of peer-reviewed, high-quality academic sources.

To ensure the relevance and suitability of the literature, the potential articles were individually reviewed according to the following criteria: 1) consistency of the functional unit within the study; 2) inclusion of environmental assessments of reuse or recycling processes; 3) presence of global warming potential (GWP), embodied carbon emissions (ECE), or greenhouse gases (GHG) data; 4) extension of the system boundary to include LCA Module D, beyond the current system boundary; 5) incorporation of result comparisons between scenarios, such as the environmental impact of recycling compared to reuse; and 6) inclusion of full-scale building cases rather than single materials or building components. Studies meeting all six criteria were considered eligible, while those failing to meet any of the above requirements were excluded from the meta-analysis.

Fig. 2 presents the literature search and screening procedure, detailing the number of articles identified, excluded, and included at each stage. Initially, 406 articles were retrieved from two databases. After removing 133 duplicates, 273 unique articles remained. A preliminary evaluation was then conducted by reviewing the titles, abstracts, and article types, leading to the exclusion of 106 articles unrelated to buildings and 23 review articles, comments, and letters. The remaining articles underwent a full-text evaluation based on the 6 predefined criteria, resulting in the exclusion of 126 articles. Specifically, 9 articles were excluded due to inconsistencies in the functional unit, 7 articles lacked an environmental impact assessment of reuse or recycling processes, 11 articles did not report GWP, ECE, or GHG data, 21 articles failed to incorporate LCA Module D, 52 articles did not include scenario comparisons, and 26 articles focused on individual materials or building components rather than full-scale buildings. Ultimately, 18 articles met all inclusion criteria and were used for the comparative meta-analysis.

2.2. *Partial harmonization*

To generalize the findings of multiple LCA studies, we employed the partial harmonization method proposed by Peng et al. (2022) to perform the meta-analysis. Specifically, the functional units, system boundaries, allocation approaches, and upstream processes were made consistent across studies, as presented in Table 1. Specifically, the functional unit was unified as the environmental impact per square meter (m^2), as

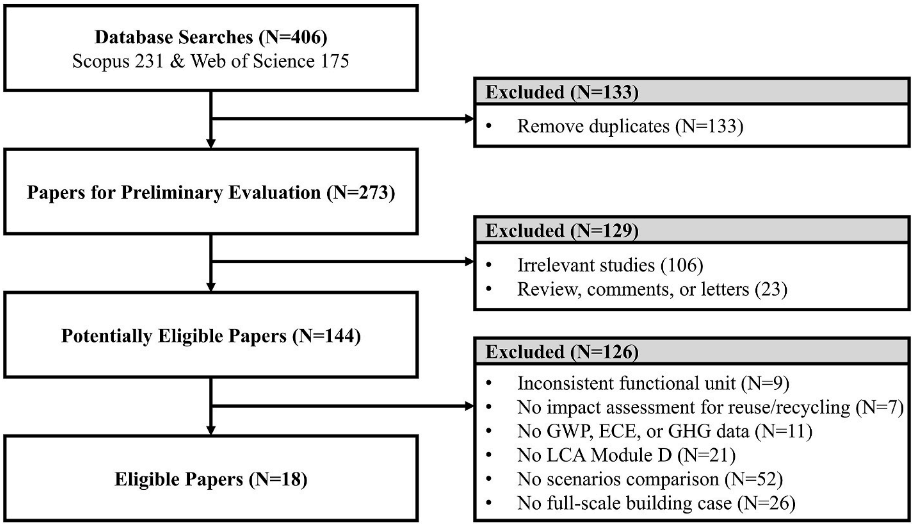


Fig. 2. PRISMA diagram for screening the papers.

Table 1
Partial harmonization for the LCA studies.

Inconsistency	Harmonization for the meta-analysis	Processes
Functional unit	Unify the functional unit to the environmental impact per square meter (m^2)	Use the reference data provided in each study to calculate the environmental impact equivalent to the unified functional unit.
System boundary	Consider a system boundary of “cradle-to-cradle” and quantify the overall net environmental impacts.	Include production (Module A), end-of-life (Module C), and benefits/loads beyond the system boundary (Module D). Exclude operation (Module B).
Allocation	Apply the avoided burden approach.	Consider the environmental benefits of the potential recycling or reuse and accredit it in the first life cycle.
Upstream	Include raw material extraction and transportation, and assume all materials are virgin.	Include the upstream processes if the original study is missing.

nearly half of the shortlisted studies adopted it. For studies with varying functional units, the results were converted by calculating the environmental impact per square meter. This was done by dividing the total environmental impact by the floor area of a building. It is essential to unify the functional unit in the comparative meta-analysis, as it ensures the comparability of different LCA studies and enables meaningful generalization of results. Regarding the system boundary, we considered a single life cycle from "cradle to cradle", including modules A, C, and D, while module B was excluded, as embodied impacts were evaluated in the present meta-analysis. In terms of the allocation approach, the avoided burden approach (0:100 approach) was adopted, as it is widely used for quantifying the environmental benefits of material recovery and reuse. This approach credits the environmental benefits of avoiding virgin material production to the current life cycle, while considering the corresponding environmental burden, allowing a clear comparison of which EoL scenario provides greater benefits (Allacker et al., 2017). Notably, some studies incompletely reported the environmental impacts of upstream processes. Therefore, we supplemented the environmental impact of this stage by using the emission factors and their material quantities provided by these studies. The resultant environmental impacts were presented as GWP in kg CO_2-equivalent. The partial harmonization processes provided generalized environmental impact results by reducing inconsistencies arising from LCA methodological discrepancies.

2.3. Full harmonization

LCA studies on building reuse and materials recycling often involve various geographical, temporal, and technological contexts, leading to differences in inventory data across studies (Nitschelm et al., 2016; van der Giesen et al., 2020). Based on the partial harmonization, we further harmonized inventory data and the LCIA method to recalculate the

Table 2
Full harmonization for the LCA studies.

Inconsistency	Harmonization for the meta-analysis	Processes
Functional unit	Unify the functional unit to the environmental impact per square meter (m^2)	Use the reference data provided in each study to calculate the environmental impact equivalent to the unified functional unit.
System boundary	Consider a system boundary of “cradle-to-cradle” and quantify the overall net environmental impacts.	Include production (Module A), end-of-life (Module C), and benefits/loads beyond the system boundary (Module D). Exclude operation (Module B).
Allocation	Apply the avoided burden approach.	Consider the environmental benefits of the potential recycling or reuse and accredit it in the first life cycle.
Upstream	Include raw material extraction and transportation, and assume all materials are virgin.	Include the upstream processes if the original study is missing.
Inventory data	Use consistent inventory data.	Select corresponding inventory data from the Ecoinvent v3.11 database based on the geographical location of each case study, using GLO or RoW data if regional data are unavailable.
Foreground data	Introduce uncertainty analysis and a material data imputation mechanism	Conduct uncertainty analysis to generate probabilistic results when some foreground data are missing; and apply a material imputation mechanism to fill in missing information about material grades and specifications.
LCIA method	Apply the ReCiPe 2016 midpoint method (H).	Use the ReCiPe 2016 V1.03 midpoint method for datasets’ impact assessment.

environmental impacts of the shortlisted studies. The harmonized aspects are summarized in Table 2. Specifically, inventory data were sourced from the Ecoinvent V3.11 cut-off database. The Ecoinvent database provides inventory data covering multiple countries and regions. When regional data were available, the inventory data were selected based on the geographical location of each study to ensure accuracy in the analysis. However, if regional data were unavailable, GLO (global) or RoW (rest of the world) data were used for the environmental analysis. Regarding the LCIA method, we adopted the widely used ReCiPe 2016 V1.03 midpoint method for calculating the environmental impact of specific materials. The ReCiPe method was adopted because it is one of the most advanced LCIA methods, encompassing the broadest range of impact categories, and it has been widely used in LCA studies and incorporated into the European standard (EN 15804, 2021; Rashedi and Khanam, 2020). The midpoint method was chosen over the endpoint one, as the latter provides a single score that may be influenced by the subjective weighting parameters in life cycle impact assessment, affecting the accuracy of the results (Dong and Ng, 2014). Finally, the environmental impact calculation was conducted at the building level, following the European standards EN 15978; EN 15804, and building LCA guidelines (Gervasio and Dimova, 2018). The inventory data queries, processing, modelling, and calculations were conducted using OpenLCA software version 2.4.0.

We recalculated the environmental impacts for each case based on the foreground data and EoL scenarios provided in the individual studies. Specifically, the foreground data included material quantities (see Supplementary Materials Sheets 2 and 4), transportation distances, material flows (e.g., reuse/recycling rates), and EoL treatment routes. These data were directly extracted from tables and supplementary materials in the original studies, which were not modified. Notably, some studies provide bills of material quantities without specifying the classification or specifications of the materials. For example, concrete has multiple grades, ranging from C20 to C100, while steel grades typically span from S235 to S690, each with distinct compositions and environmental impacts (Lin et al., 2025; Skoglund et al., 2020). However, only a few studies (e.g., Greene et al., 2023; Passarelli and Mouton, 2023) explicitly provided material classifications and specifications, while others did not include these details. To address this issue, we implemented a material data imputation mechanism to fill in missing information. When a specific material and its classification were provided in a study, we used the corresponding inventory data for that material. If a material classification was not specified, we considered the most common material type and grade instead. For instance, if the concrete grade was not mentioned, C30, the most widely used concrete grade, was considered for impact assessment. A similar treatment was applied to other materials as well. Additionally, some papers failed to provide information on transportation, material input, and output flows. In cases where specific data were lacking, transport scenarios provided by Lei et al. (2023a) and Wang et al. (2024) were adopted. Reuse and recycling rates were also collected from each case study where available. In the absence of such data, we assigned random values for specific materials (Yang et al., 2024). A Monte Carlo simulation was also conducted to capture the uncertainty arising in reuse/recycling rates and transport distances. Specifically, such an uncertainty analysis was only conducted to produce probabilistic results when some foreground data are missing (The analyzed results included probabilistic LCA outcomes, see Supplementary Materials Sheets 1 and 3). Although this process is resource-intensive, it is worthwhile to derive probabilistic results instead of deterministic ones, as the former better captures the impact of uncertain inputs on LCA outcomes as well as the meta-analysis results. Additionally, the comparative meta-analysis includes different types of buildings, involving various building materials and components. Therefore, it is essential to distinguish end-of-life treatment routes for different building materials and components. For instance, the recycling processes for concrete and mass timber components are considered separately based on their specific EoL treatment routes. Specifically, concrete components typically undergo downcycling, whereas mass timber components may involve downcycling, upcycling, and/or incineration processes.

2.4. Comparative analysis

In the present research, the environmental impacts of three scenarios were compared: reuse, recycling, and landfilling. The landfilling scenario represents conventional CDW treatment practices, where all demolition wastes are directly sent to landfills without any recovery or value-retaining processes. The recycling scenario includes recycling materials as the predominant strategy and disposal of non-recyclable wastes as the secondary strategy. The reuse scenario contains the reuse of building components and materials as a predominant strategy and the recycling of non-reusable materials as the secondary strategy, followed by landfilling. Based on these three scenarios, the authors conducted pairwise comparisons of the environmental impacts between recycling and landfilling scenarios, and between reuse and recycling scenarios.

We used an environmental impact ratio (GWP%) to measure the relative environmental impacts of recycling compared to landfilling (Eq. (1)), and the relative environmental impact of reuse compared to recycling (Eq. (2)). A smaller GWP% indicates a better environmental benefit of recycling or reuse scenarios compared with its counterpart.

The environmental impact of the recycling scenario relative to the landfilling scenario

$$GWP\% = \frac{EI^{per\ FU}_{recycling.}}{EI^{per\ FU}_{landfilling}} \times 100\% \qquad \text{Eq. (1)}$$

The environmental impact of the reuse scenario relative to the recycling scenario

$$GWP\% = \frac{EI^{per\ FU}_{reuse}}{EI^{per\ FU}_{recycling}} \times 100\% \qquad \text{Eq. (2)}$$

Where: GWP% is the environmental impact ratio between scenarios; $EI^{per\ FU}_{landfilling}$, $EI^{per\ FU}_{recycling}$, $EI^{per\ FU}_{reuse}$ indicates the net environmental impact of landfilling, recycling, and reuse scenarios for each functional unit, respectively.

We further calculated the mean GWP% of all studies. Some shortlisted studies (Passarelli and Mouton, 2023; Tanthanawiwat et al., 2024) conducted uncertainty analyses and reported probabilistic LCA results, while others (Eberhardt et al., 2019; Wang et al., 2018) provided multiple results for a given EoL scenario. To determine the mean and 1.5 times the interquartile range (1.5 IQR) of GWP% of all studies, a Monte Carlo simulation was conducted. This simulation was performed using Python 3.8.5 in PyCharm. These statistical analyses provided comprehensive insights into the environmental impacts across multiple EoL scenarios for buildings by synthesizing the individual studies.

2.5. Sensitivity analysis

To assess the influence of parameter changes on the output ‘GWP%’, a One-at-a-Time (OAT) sensitivity analysis was conducted. In this analysis, we varied the individual parameters within a range of ±20 % and recalculated the outputs (Anderson et al., 2014). The analysis specifically examined GWP% variations in two scenarios: recycling versus landfilling scenarios and reuse versus recycling scenarios. Three parameters were considered: 1) reuse rate, 2) recycling rate, and 3) transport distance. In the comparison of the reuse and recycling scenarios, the primary goal was to examine how the change in the reuse rate affected the output. Similarly, it was of interest to explore the influence of the recycling rate on the output when comparing recycling with landfilling scenarios. In these cases, the transport distances from the site to reuse storage/recycling facilities and to landfills were considered.

Three major building materials were chosen for the OAT analysis: concrete, steel, and timber, as they were the main building materials analyzed in selected studies. Notably, the sensitivity analysis was only presented for the meta-analysis with fully harmonized LCA methods, as the results for full and partial harmonization processes were found identical. The sensitivity analysis was performed in the PyCharm IDE using a Python 3.8.5 environment, and the resulting data were fitted using OriginPro 2024b.

2.6. Robustness test

Given the many assumptions involved in the harmonized LCA method, it is crucial to test the robustness of the meta-analysis results when these assumptions are altered. In this study, we focused on four key aspects: (1) foreground data, (2) inventory data, (3) EoL modelling approaches, and (4) LCIA methods. The meta-analysis outcomes arising from the full harmonized LCA method were selected as the baseline scenarios.

Foreground data on the physical properties of products can vary by material due to differences in specifications and manufacturing techniques. However, many of the selected LCA studies did not provide specific material grades and specifications. In these cases, commonly used material grades were assumed. For example, in the preliminary meta-analysis, concrete was assumed to be grade C30 and steel was treated as ungraded and modeled as "steel, unalloyed" (as a baseline scenario). However, these assumptions could affect the results of the meta-analysis. To address this, the study further examined whether material selection influences the validity of the meta-analysis outcomes by comparing the environmental impact ratios of different material grades. Specifically, medium-grade materials C40 and S460, as well as high-grade materials C50 and S690, were used to replace the baseline scenario in order to test the validity of the meta-analysis results.

In the preliminary meta-analysis, local datasets from Ecoinvent were used for environmental analysis whenever available. When local datasets were not accessible, global datasets served as substitutes. In other words, a combination of local and global datasets from Ecoinvent was used in the baseline scenario. To further evaluate how the type of datasets affects the meta-analysis outcomes, we compared the results obtained using only global datasets with this baseline scenario.

The most widely used EoL modelling approaches include cut-off (100:0), avoided burden (0:100), and equal distribution (50:50) (Allacker et al., 2017; Antwi-Afari et al., 2023; Yang et al., 2024). The 100:0 approach allocates the environmental benefits of reuse and recycling to the production process of the existing system, while not considering the burdens of reuse or recycling. It encourages policymakers and practitioners to focus on reusing previously used products within the current life cycle. The 0:100 method allocates both environmental benefits and burdens to the existing system, prompting policymakers and practitioners to consider reuse and recycling at the end of the current life cycle. The 50:50 approach divides the environmental benefits and loads of reuse or recycling equally between the current and subsequent life cycles, which promotes reuse and recycling during both production and end-of-life stages. The 0:100 approach was initially used in the meta-analysis because it tends to "maximize" the environmental advantages of reuse and recycling by attributing all environmental benefits to the existingsystem. Given that different EoL modelling approaches may lead to various practical implications, this study tested whether they could influence the validity of the meta-analysis outcomes.

The ReCiPe 2016 mid-point method was initially employed in the meta-analysis. The study further tested the robustness of the meta-analysis by changing LCIA methods. Three LCIA methods were considered, including IPCC 2021, ReCiPe 2016 midpoint, and CML V4.8. IPCC 2021and ReCiPe 2016 midpoint were selected as they were most frequently applied in the selected studies, while CML was included because it is mentioned in the standard EN 15804. Therefore, the meta-analysis results were compared among these three methods. Notably, the robustness test was conducted using a One-at-A-Time approach, in which one aspect was altered while the other three aspects remained based on the initial assumptions.

3. Results

3.1. Overview of the literature

The meta-analysis was performed on 21 building cases sourced from 18 selected studies, including both peer-reviewed articles and conference proceedings. Basic information about these cases and studies can be found in Appendix Table A3. The selected papers primarily originated from China, Australia, the United States, Asian countries, and European countries. As illustrated in Fig. 3, the number of publications has increased, with a notable concentration of publications in recent years. Specifically, more than half of others (12 out of 18) were published over the past five years. This trend suggests an increasing academic focus on the environmental impacts of building reuse and recycling strategies, reflecting a growing interest in the circular economy in the construction sector.

The background information of the LCA studies is illustrated in pie charts in Fig. 4. It summarizes the building type, functional unit, database, and LCIA method adopted in the selected studies. The 21 building cases covered common building types, including conventional concrete buildings, steel frame buildings, mass timber buildings, DfD buildings, DfD modular buildings, and concrete and timber houses (Fig. 4(a)). For the choice of functional unit, eight studies selected environmental impact per square meter as the functional unit (Fig. 4(b)). Seven authors defined the functional unit as the whole building or the whole analyzed unit, while two others used material quantities. Notably, the two authors combined lifespan and floor area as the functional unit. For instance, Tulevech et al. (2018) defined the functional unit as ‘per square meter per year’. Fig. 4(c) depicts the LCA databases used in the studies. Nearly half of them (8 out of 18) utilized the Ecoinvent database (including Ecoinvent V3.0, V3.3, V3.5, and V3.7), followed by ELCD (3 papers). While nine studies specified the LCA database used, the exact versions of the databases were not clarified. In terms of the LCIA method, the IPCC 100 method was most frequently employed, followed by ReCiPe midpoint and Baseline methods (Fig. 4(d)). However, it should be noted that six papers did not specify the LCIA method used for analysis. Apparently, incomplete LCA data and information from individual studies have made it difficult to generalize the environmental benefits of building reuse and recycling.

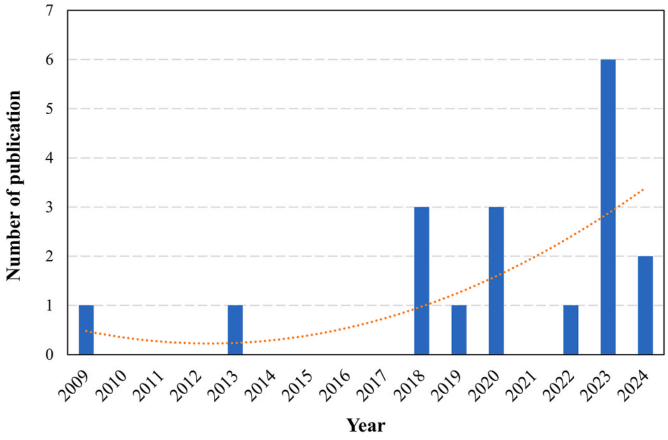
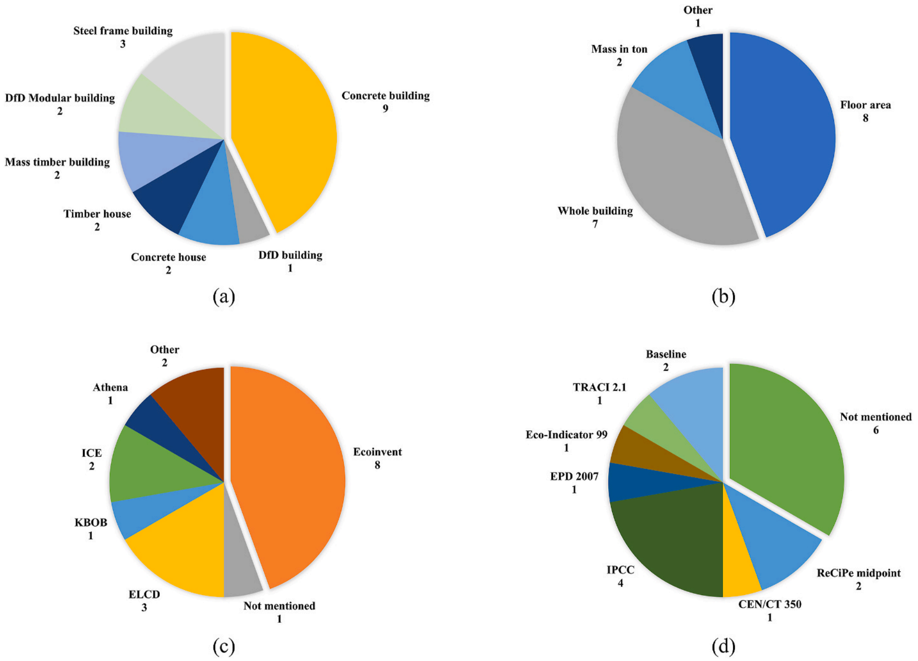


Fig. 3. Number of publications by year. (**Note**: The orange dashed line represents the fitted trend line, indicating the variation in the number of publications by years).



(a) (b) (c) (d)

Fig. 4. Details of the selected LCA studies: (a) building type, (b) functional unit, (c) LCA database, and (d) LCIA method.

3.2. Results of the meta-analysis

Figs. 5 and 6 present the results of the meta-analysis based on partial and full harmonization processes, which provide information about the GWP% differences between recycling and landfilling scenarios, and between reuse and recycling scenarios. The Y-axis of Figs. 5 and 6 annotates the buildings' main structure and quantity proportion of primary materials. Specifically, Fig. 5 shows the GWP% as the environmental impact ratio of recycling and landfilling scenarios. In this context, a ratio below 100 % indicates that the recycling scenario is environmentally preferable to its counterpart. The same approach was applied to compare the environmental impact of reuse and recycling scenarios (Fig. 6). Detailed original, partial-harmonized, and full-harmonized LCA results are provided in the Supplementary Material Sheet 1 and Sheet 3. Notably, some results are presented with error bars in the two figures. For partial harmonization, this is because some studies (Passarelli and Mouton, 2023; Tanthanawiwat et al., 2024) conducted uncertainty analyses and provided probabilistic results, while others (Eberhardt et al., 2019; Wang et al., 2018) reported multiple results for a given EoL scenario. As for full harmonization, we conducted uncertainty analyses for studies (Blengini, 2009; Eberhardt et al., 2019; Greene et al., 2023; Jayawardana et al., 2023; Passarelli and Mouton, 2023; Tanthanawiwat et al., 2024; Tulevech et al., 2018; Wang et al., 2018, 2024) that did not provide complete foreground data, and the probabilistic results were given.

Fig. 5 depicts the GWP% of recycling and landfilling scenarios. The results indicated that the environmental impact of recycling compared to landfilling scenarios ranged from 12 % to 97 % based on the partial harmonization approach. This ratio ranged from 51 % to 89 % after full harmonization of LCA studies. Despite this, the results of the meta-analysis show that, regardless of partial or full harmonization of LCA studies, the recycling scenario exhibits less environmental impacts compared to its landfilling counterparts. The environmental benefits of building recycling largely depend on the materials used. In the current study, we quantified the specific materials and their amounts for each case study and evaluated the environmental benefits of recycling various materials (results available in Supplementary Material Sheet 2). The results indicate that, with the full harmonization method, the recycling of metallic materials (e.g., structural steel, rebar, and aluminum) and wood tend to yield greater environmental benefits compared to the recycling of concrete. However, only limited case studies involved heavily used metallic and wooden materials (e.g., Lei et al., 2023b; Tanthanawiwat et al., 2024; Tulevech et al., 2018), which may introduce research bias for the meta-analysis.

Fig. 6 shows the GWP% of reuse and recycling scenarios. It shows that the GWP% ranged from 6 % to 89 % based on a partial

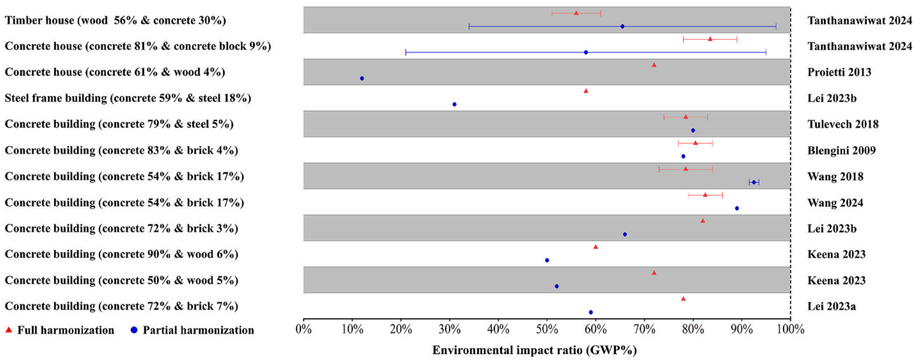


Fig. 5. Environmental impact ratio of recycling versus landfilling scenarios.

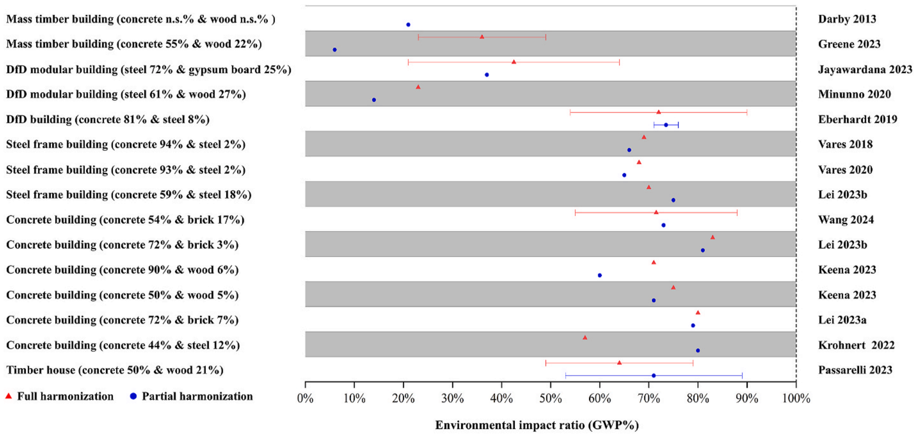


Fig. 6. Environmental impact ratio of building reuse versus recycling scenarios.
Note: The study by Darby et al. (2013) was excluded from the full harmonization process due to a lack of material inventory of the building.

harmonization of LCA studies. Such a range did not significantly change when LCA studies were fully harmonized, i.e., 21 %–90 %. Overall, the results of the meta-analysis indicate that the environmental impacts associated with reusing building materials/components are lower than those from recycling. Notably, such benefits can vary across different building design methods and materials, the specific results can refer to Supplementary Material Sheet 4. As shown in Fig. 6, the environmental benefits of reusing mass timber and DfD modular buildings tend to be more remarkable than those of reusing conventional concrete and steel frame buildings.

The mean environmental impact ratios are depicted in Fig. 7. The environmental impact of recycling scenarios was 61.1 % and 73.5 % of that of landfilling scenarios when LCA studies were partially and fully harmonized, respectively. Meanwhile, the environmental impact of reuse scenarios compared with recycling scenarios was 58.2 % and 62.9 % when LCA studies were partially and fully harmonized, respectively. The results indicate that, compared to the partial harmonization method, the environmental benefits were less significant when using the full harmonization method. Moreover, the comparison between recycling and landfilling scenarios indicated the fully harmonized results deviated by around 12 % from those obtained through partial harmonization, showing the influence of inventory data and the LCIA method on the meta-analysis outcomes.

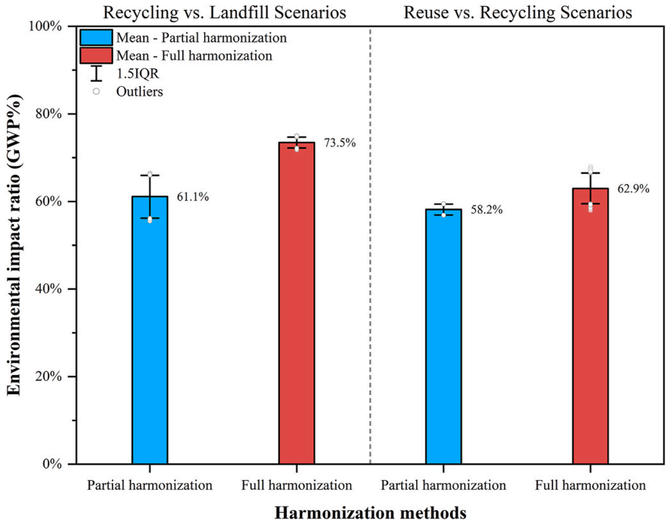


Fig. 7. Meta-analysis based on partial and full harmonization of LCA studies.

3.3. Results of sensitivity analysis

Fig. 8 depicts the sensitivity of the output variance to parameter changes when comparing recycling with landfilling scenarios (with the full harmonization method). The results indicate that the material's recycling rate becomes the most influential parameter. Among the three building materials tested, steel and wood demonstrate higher sensitivity to variations in recycling rates compared to other inert materials like concrete. Specifically, the change in recycling rates of steel and wood by 20 % could potentially influence the output variance by up to around 1.6 %. The results suggest that increasing the recycling rates of steel and wood could significantly enhance the benefits of recycling compared to landfilling. In contrast, raising the recycling rates of concrete may not yield substantial recycling benefits. Additionally, changes in transport distance have a minimal impact on output variation. The sensitivity analysis further revealed that a 20 % change in the recycling rate for concrete resulted in only a 0.63 % variation in output. Similarly, a 20 % change in transport distance led to a 0.3 % variation. These results suggest that adjustments in the recycling rate for concrete and transport distance have a minimal impact on enhancing the environmental benefits of recycling compared to landfilling.

The sensitivity of the parameter changes to output variation, when comparing reuse with recycling scenarios based on the full harmonization method, is illustrated in Fig. 9. Similarly, it is observed that the material's reuse rate is the most critical parameter affecting output variation. Specifically, a 20 % change in the reuse rate of concrete, steel, or timber may result in approximately 2 %–2.5 % change in output. In contrast, alterations in transport distance have a minimal impact on the benefits of reuse, with a 20 % change in transport distance resulting in only about a 0.1 %–0.2 % change in the output.

3.4. Results of robustness test

3.4.1. Variation of foreground data

Fig. 10 illustrates the impact of foreground data on the meta-analysis results by examining different grades and types of concrete and steel. The findings show that using higher-grade materials leads to greater environmental benefits from recycling and reuse, although the differences between them are not substantial.

3.4.2. Variation of inventory data

Fig. 11 illustrates how different types of inventory data influence the meta-analysis results. Specifically, when comparing recycling to landfill scenarios, using global data in all selected studies shows a lower environmental benefit than using both local and global data (global data were used only when local data were not available), with a higher

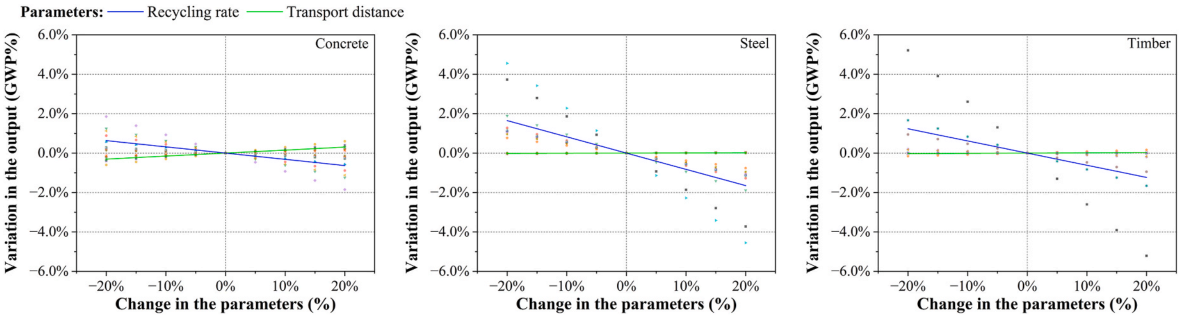


Fig. 8. Variation in GWP% (Comparison of recycling and landfilling scenarios).

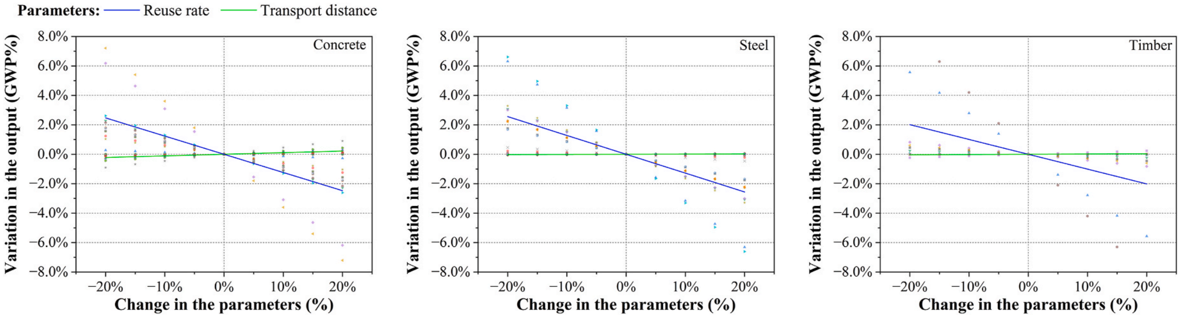


Fig. 9. Variation in GWP% (Comparison of reuse and recycling scenarios).

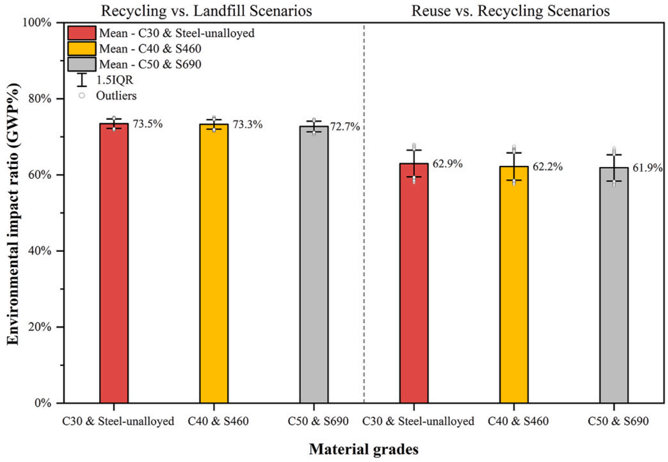


Fig. 10. Influence of different material grades and types on environmental impact ratios.

Note: Red bars represent the baseline scenario, where the full harmonization method was applied. The horizontal axis represents different grades and types of concrete and steel. For instance, C30 represents concrete with a compressive strength of 30 MPa, while S460 denotes steel with a yield strength of 460 MPa. A combination of C30 & steel-unalloyed, C40 & S460, and C50 & S690 represents normal, medium, and high-grade materials. In addition, due to the lack of inventory data on steel grades in the Ecoinvent database, the inventory data for high-performance steel was obtained from another ongoing study by Hussain et al. (2025).

environmental impact ratio of 74.9 %. However, when comparing reuse to recycling scenarios, global data indicates a slightly higher environmental benefit than the combination of local and global data. Despite these variations, the differences between using local and global data might not significantly influence the interpretation of recycling and reuse benefits in terms of environmental impacts.

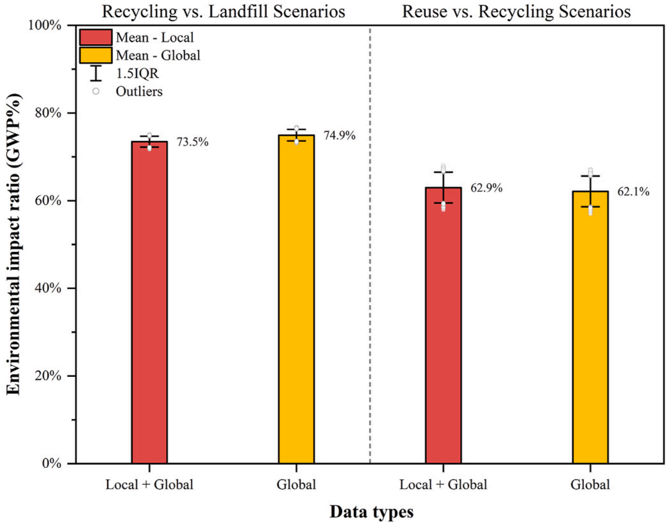


Fig. 11. Influence of different inventory data on environmental impact ratios.

Note: Red bars represent the baseline scenario, where the full harmonization method was applied.

3.4.3. *Variation of EoL modelling approaches*

The baseline scenario (0:100 approach) demonstrates the highest environmental benefits for both recycling and reuse, accompanied by the lowest environmental impact ratios among all EoL modelling methods (Fig. 12). However, these benefits gradually decline when applying the 50:50 and 100:0 approaches. Specifically, the 50:50 approach results in a decrease in the environmental benefits of recycling and reuse by approximately 10 %–20 % compared to the baseline. In contrast, the 100:0 approach yields environmental impacts from reuse and recycling that are nearly equal to their alternatives. For instance, the environmental impact of recycling is 94.2 % that of landfill, while the impact of reuse is 94.5 % that of recycling. In view of this, the EoL

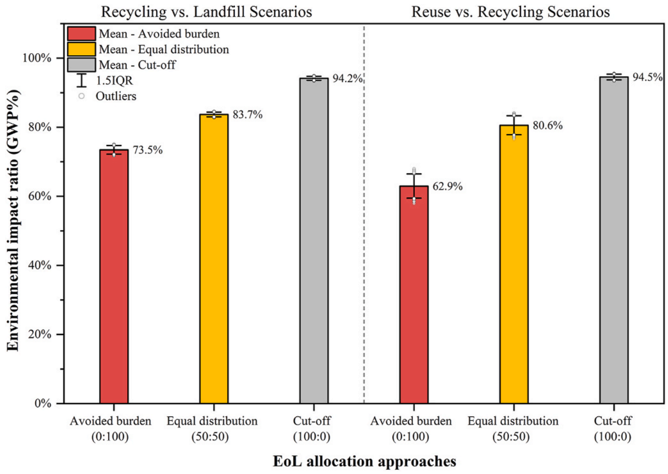


Fig. 12. Influence of different EoL modelling approaches on environmental impact ratios.
Note: Red bars represent the baseline scenario, where the full harmonization method was applied.

modelling significantly affects the allocated environmental benefits and burdens of reuse, recycling, and landfill, leading to notable changes in environmental impact ratios across different EoL approaches.

3.4.4. Variation of LCIA methods

Fig. 13 shows that changes in LCIA methods have a minimal impact on the meta-analysis results, as the variation in environmental impact ratios across the three LCIA methods is limited to just 1 %. This finding aligns with the observations of Karolinczak et al. (2024), who noted an approximate 2 % difference in results for GWP when using both the ReCiPe and CML methods.

4. Discussion

4.1. Influence of partially and fully harmonized LCA methodologies

The use of a meta-analysis of LCA studies has been challenged by inconsistent LCA methodologies used in individual studies (Deeney et al., 2023; Peng et al., 2022; Tu et al., 2017). This study affirms this point of view. To address this issue, separate meta-analyses have been conducted when the individual LCA studies were partially and fully harmonized. The outcomes of the meta-analysis indicate that the environmental benefits of recycling and reuse are amplified in the partial harmonization scenario compared to the full harmonization one. The differing outcomes of the meta-analyses based on partial and full harmonization approaches are mainly attributed to non-harmonized inventory data and LCIA methods. The results reveal the differences in the meta-analysis outcomes between partial and full harmonization approaches, offering a fresh insight into how LCA methodologies affect the meta-analysis outcomes.

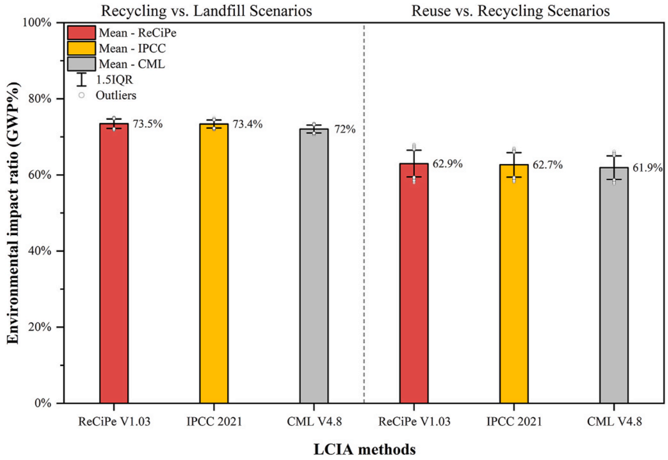


Fig. 13. Influence of different LCIA methods on environmental impact ratios.
Note: Red bars represent the baseline scenario, where the full harmonization method was applied.

To enable a rigorous meta-analysis of LCA studies, this study applied the partial harmonization method to unify various aspects of LCA methodologies, including the functional unit, allocation methods, system boundaries, and upstream processes. This partial harmonization method is essential for the current meta-analysis, as different LCA methodologies make EoL scenarios incomparable to generalize findings on the extent to which reuse and recycling benefit the environment. To address these challenges, the current study reduces inter-study heterogeneity by unifying system boundaries, functional units, impact allocation methods, and upstream processes. Such a partial harmonization process facilitates a better understanding of the environmental benefits of various EoL scenarios.

Apart from the above methodological heterogeneity, inconsistencies were also found in the inventory and LCIA methods among the individual LCA studies. Previous studies have preliminarily utilized partial harmonization methods to address methodological heterogeneity across LCA studies (Fan and Fang, 2023; Minunno et al., 2021; Thonemann, 2020). However, they have failed to adequately address the heterogeneity in inventory data. To make data sources consistent, this study used consistent inventory data, the LCIA method, and calculation procedures to evaluate the environmental impact of EoL strategies. It is advised that consistent inventory data and the LCIA method are important for reducing data heterogeneity among LCA studies to obtain generalized meta-analysis outcomes (Tu et al., 2017; Peng et al., 2022). Some studies also emphasized that consistent inventory data, LCIA methods, and calculation procedures can reduce variations in LCA analyses, thereby offering a clearer understanding of overall trends in the environmental impacts of a process or product (Meron et al., 2016; Tu et al., 2017). By doing so, this paper offers new insights into the meta-analysis to ascertain the generalized environmental benefits of reuse and recycling using partial and full LCA harmonization methods.

It is well recognized that localized or site-specific inventory data can provide more reliable decision-making in a LCA study compared to global data. However, obtaining fully localized data requires significant effort in collecting local information, defining varying localized scenarios, and replacing global data to validate the results (Dong et al., 2015). Due to the lack of localized inventory data, prior research has often relied on global data. For example, Tulevech et al. (2018) used Ecoinvent 3.0 to assess the environmental impact of building recycling in Thailand, while Ecoinvent 3.0 primarily included inventory data for Europe. To address the challenge of limited localized inventory data, most previous LCA studies have utilized a mix of local and global data. In this meta-analysis, we harmonized the inventory data using a similar approach adopted by Tu et al. (2017), which may diminish the region-specific characteristics of the LCA studies. This is considered an important limitation of the research. However, it is essential to note that the aim of this study is not to identify which harmonization methods yield more accurate results. Instead, it seeks to enhance understanding of how different levels of harmonization in LCA methods influence meta-analysis outcomes.

4.2. Influence of construction materials and building design methods

4.2.1. Recycling vs. landfilling

The environmental impacts of recycling scenarios average 73.5 % of those of landfilling scenarios (with full harmonization of LCA methodologies), highlighting the environmental benefit of recycling compared to landfilling. In the meta-analysis of 12 cases, the majority of construction materials analyzed include concrete, which accounts for 30 %–90 % of the total material weight. Recycling inert materials, such as concrete, bricks, and blocks, results in lower environmental impacts than landfilling, which aligns with previous studies (Tam, 2008). However, this study indicates that the benefits of recycling may be minimal, as the environmental impacts of recycling concrete buildings are reported to be around 71 %–96 % of those associated with landfilling. The relatively low recycling rate of a large number of inert materials, as low as 5 %, may contribute to the small difference in the environmental impacts between recycling and landfilling. This may help explain that disposal remains preferable to concrete recycling in practice probably because the latter has contributed to relatively small environmental benefits. While the recycling rate of inert materials can exceed 90 % in some developed countries (Jin and Chen, 2019), it remains below 10 % in developing nations (Zhang et al., 2023). This lower recycling rate leads to a greater volume of construction waste that must be disposed of. Even though over 90 % of inert materials can be recycled in certain cases, the durability of these recycled materials is inferior to virgin materials (Ma et al., 2022). Consequently, recycled materials are typically applied in non-structural components, road pavement, or as partial substitutes for raw materials in new production processes. They exhibit low value-added materials. Accordingly, the environmental gains associated with the avoidance of the production of new materials replaced by low-value-added materials may be diminished.

The results of the meta-analysis indicate that the environmental benefits of recycling steel-framed buildings and timber houses are more significant than those of recycling concrete buildings. The recycling of structural steel has long been recognized for its substantial contributions to environmental savings compared to landfilling. It is relatively easy to separate steel from other materials, facilitating collection and sorting. Currently, the global recycling rate of steel exceeds 90 %, and recycled steel can effectively replace virgin materials. Such a high recovery efficiency reduces disposable waste and decreases the need for virgin materials. As a result, recycling steel leads to considerably lower environmental impacts than landfilling.

Consistent with the findings of Hossain and Poon (2018), this study demonstrates that recycling wood materials offers greater environmental benefits compared to landfilling. On the one hand, when wood materials are disposed of in landfills, aerobic oxidation produces carbon dioxide (Diyamandoglu and Fortuna, 2015), resulting in a higher environmental impact. On the other hand, recycling wood materials decreases the consumption of virgin materials, resulting in a lower net environmental impact than landfilling. However, the environmental benefit of wood recycling can be influenced by material recovery efficiency, the extent to which recycled wood can replace virgin materials (Di Maria et al., 2018).

4.2.2. Reuse vs. recycling scenarios

The present findings indicate that the environmental impacts of reuse scenarios average 62.9 % of that of recycling scenarios (with full harmonization of LCA methodologies), suggesting that reusing building components is more environmentally preferable than recycling. However, the specific construction materials and methods selected can influence the environmental impacts of reuse compared to recycling. This study offers fresh insights into environmentally viable EoL strategies for different building types. Among the construction methods examined, the benefits of reusing mass timber and DfD modular buildings, measured as the ratio of the environmental performance of reuse to that of recycling, are found to be more substantial than those of reusing other types of buildings. Specifically, the environmental impacts of mass timber and DfD modular buildings are less than half of those impacts of recycling.

Past studies have demonstrated that mass timber buildings emit less than half of the environmental impact of conventional concrete buildings and steel-framed buildings (Allan and Phillips, 2021; Younis and Dodoo, 2022). This is primarily due to the high levels of carbon stored in timber, which leads to lower carbon dioxide emissions during the production process (Younis and Dodoo, 2022). When carbon sequestration is considered in timber products, the production stage of mass timber often results in negative carbon emissions, as the biogenic carbon is assumed to be withdrawn from the atmosphere (Younis and Dodoo, 2022). The characteristics help reduce the carbon footprint of mass timber buildings and contribute to achieving sustainable development goals (SDGs). On one hand, timber absorbs significant amounts of carbon dioxide during growth, functioning as a carbon sink, which helps mitigate climate change and aligns with SDG goal 13 (Climate Action). On the other hand, massive timber elements can be reused or recycled at the EoL stage (Duan et al., 2022), supporting the principles of a circular economy and aligning with SDG goal 12 (Responsible Consumption and Production).

Additionally, mass timber buildings offer a viable pathway for meeting circular economy principles and achieving net-zero goals. Numerous studies have explored the use of mass timber in building design to reduce carbon emissions at the production stage and highlighted the adoption of reuse strategies at the end-of-life stage to support net-zero goals (Ahmed et al., 2024; Felmer et al., 2022; Greene et al., 2023). For instance, Greene et al. (2023) present a notable case that integrates sustainable strategies across all life cycle stages. The building features a full timber structure, supplemented by solar arrays to offset operational emissions and an extensive reuse and recycling strategy at EoL, resulting in near-zero life cycle emissions, with net emissions as low as 5 kg CO_2-eq/m^2. Due to its all-timber design, the building is lighter than conventional concrete and steel designs, facilitating installation, disassembly, and transportation. Additionally, the use of demountable steel connections further enhances easy disassembly and avoids damage. As a result, approximately 95 % of the structural timber (timber beams and columns) and 75 % of the cross-laminated timber could be directly reused. This case highlights the high reuse potential of mass timber buildings, demonstrating their ability to reduce environmental impact and offer benefits. By integrating circular economy principles and net-zero design strategies, mass timber buildings can play a crucial role in climate change mitigation and resource efficiency.

Reusing timber results in a significantly lower net environmental impact compared to recycling and landfilling because it facilitates the longer-term storage of embodied biogenic carbon (Greene et al., 2023). In terms of recycling, used timber is typically recycled into products like chipboard, particleboard, or composed wood products (Piccardo and Hughes, 2022; Tanthanawiwat et al., 2024). Its environmental impact related to the recycling of timber during remanufacturing may somehow offset the environmental gains associated with the avoidance of the production of similar new products. Despite this, the impact of reuse of timber remains less than that of recycling probably because of the extra environmental impact arising from the recycling process.

While it has been found that mass timber construction can lead to significant environmental savings during the production phase, the net environmental impact of its EoL scenarios can be uncertain. This uncertainty arises because assessment results depend on factors such as biogenic carbon storage, reuse rate, and various underlying assumptions involved in LCA. The present meta-analysis includes only two studies on mass timber buildings, and their assumptions regarding reuse scenarios tend to be “ideal” (i.e., direct reuse). Notably, there are few studies exploring current architectural practices related to the (direct) reuse of wood elements in buildings (e.g., Piccardo and Hughes, 2022). The direct reuse of mass timber buildings highly relies on the adoption of DfD principles. However, material degradation and deformation of connection systems may hinder the reuse of timber buildings (Ottenhaus et al., 2023). Future LCA studies on mass timber buildings should consider the practicality of reuse and examine the impact of uncertain reuse and/or recycling rates on the assessment outcomes. This should involve accounting for various reuse/recycling technologies applied, with the goal of providing a more holistic and robust LCA of the reuse and recycling of mass timber construction.

In general, reusing DfD modular construction results in 50 % less environmental impact compared to recycling. Key DfD approaches include the use of prefabricated modular building assemblies and demountable connections, as opposed to cast-in-place composite systems that must be demolished at the building's EoL (Eckelman et al., 2018). Several case studies have proven that reusing DfD modular buildings offers remarkable environmental advantages compared to recycling and/or landfilling (Jayawardana et al., 2023; Minunno et al., 2020). For example, Minunno et al. (2020) presented a case of DfD modular building for reusing, where steel members and demountable insulation panels were almost entirely reused at the building's end of life and could be continuously reused in subsequent life cycles. The reuse of those components reduced the GWP value by approximately 88 % compared to recycling, highlighting that DfD modular design facilitates disassembly without causing substantial structural damage to building components. By promoting the direct reuse of demountable components and preserving environmental value, DfD modular construction aligns with circular economy principles and supports SDGs by reducing (de) construction emissions.

Interestingly, the environmental impacts of reusing conventional buildings (i.e., steel-frame and concrete buildings), whether or not DfD is considered, account for around 60 %–80 % of those associated with recycling. The environmental benefits of reusing these types of buildings become smaller compared to those of reusing mass timber and DfD modular buildings. This is probably because DfD modular buildings facilitate the disassembly of building elements, which reduces the effort required for disassembly and increases the reusablity of building components. On the contrary, while conventional buildings with DfD principles allow for easy disassembly and direct reuse of building elements (e.g., concrete column, timber column) (Eberhardt et al., 2019), the reuse of these buildings still involves extensive disassembly to separate demountable layers from non-reusable parts. As a result, a relatively small reuse rate (20 %–50 %) of the DfD building (Eberhardt et al., 2019) may lead to unremarkable environmental benefits of reuse. However, this meta-analysis investigated only one article related to conventional buildings that considers the DfD strategy, which may introduce research bias.

The results of the meta-analysis ascertain that the reuse of conventional steel-framed or concrete buildings produces lower environmental impacts than recycling. However, the reuse of these conventional buildings yields relatively smaller environmental benefits compared the buildings considering the DfD strategy. This is because these conventional buildings have less potential for (direct) reuse of building components, as disassembly often causes significant damage to them. Consequently, the relatively low reuse rates of these conventional buildings, as low as 11 % (Lei et al., 2023b), may diminish the environmental benefits of reuse compared to recycling.

4.3. Influence of material recovery efficiency

The argument regarding the environmental benefits of reuse and recycling hinges on the hypothesis of material recovery efficiency, which measures how many components or materials can be reused or recycled to reduce the need for virgin materials and avoid corresponding impacts. Therefore, conducting a sensitivity analysis on how changes in reuse and recycling rates affect the environmental benefits of these processes is essential.

Our sensitivity analyses show that increasing the recycling rates of steel and wood can lead to around 1.5 % improvement in the environmental benefits of recycling compared to landfilling. Steel can be recycled to achieve almost the same quality as virgin steel. As a result, recycled steel can partially offset the environmental impact associated with producing virgin steel. In turn, this process contributes to the long-term conservation of mineral resources and reduces the reliance on raw iron ore. Moreover, recycling of scrap steel requires less energy compared to primary steel production, as it primarily utilizes energy-efficient electric arc furnaces (Diener and Tillman, 2015). This process reduces overall energy consumption and associated carbon emissions, contributing to decarbonization in the building sector and promoting environmental sustainability. Additionally, the findings confirm that increasing the recycling rate of steel enhances the environmental benefits of recycling compared to landfilling. Therefore, future efforts should optimize on-site sorting, collecting, and improving recycling technologies to further increase the environmental benefits of steel recycling. Similarly, wood is considered an environmentally preferable material (Tanthanawiwat et al., 2024), as its secondary products can somewhat offset the impact of producing new products. An increase in the recycling rate of wood can lead to greater environmental gains by reducing the need to produce new items, thereby enhancing the environmental benefits of recycling compared to landfilling. Over the long term, wood recycling can reduce dependence on raw materials and relevant carbon emissions, making it beneficial for environmental health.

However, this sensitivity is not observed with concrete, as their recycling is often considered a downcycling process. Recycled concrete is typically associated with low-value secondary material, and the environmental benefits gained from avoiding the production of raw material, replaced by these low-value materials (such as aggregates), may not be substantial. This is because the production impact of low-value secondary materials does not significantly offset the impact of creating new materials of equal quality. Supporting this inference, a previous study found that increasing the recycling rate of concrete from 27 % to 50 % could only reduce carbon emissions from buildings by 2 %–3 % (Colomer Mendoza et al., 2017). Such a small reduction may not substantially change the environmental benefits of recycling compared to landfilling. The present meta-analysis suggests that downcycling concrete offers trivial environmental benefits compared with landfilling, this may explain why demolition of concrete buildings is a common practice. In the long run, downcycling concrete cannot fully replace virgin concrete and may not reduce reliance on raw natural resources. Therefore, concrete upcycling should be actively considered. For instance, in the future, recycled concrete could be combined with new materials to produce strain-hardening cementitious composites, which is considered an upcycling process (Li et al., 2022).

Notably, a 20 % increase in the reuse rates of concrete, steel, or wood can result in approximately 2 %–2.5 % improvement in the environmental benefits of reuse compared to recycling. This is because higher reuse rates for these materials contribute to greater environmental gains by avoiding the production of equivalent components. Compared to recycling, building reuse offers a more effective way to reduce or even eliminate the demand for raw materials and resources, thereby fostering a resource-efficient society and ensuring long-term environmental sustainability (Yang et al., 2022). Empirical research suggests that adopting reuse strategies can avoid raw material production by around 20 %–50 % at each use cycle and eliminate associated emissions, collectively improving resource availability (Minunno et al., 2020; Yang et al., 2024; Zheng et al., 2025). Moreover, reuse strategies help mitigate environmental degradation linked to raw material extraction, such as deforestation and habitat destruction (Behrens et al., 2007). It is therefore concluded that priority should be given to reusing building components and materials before considering recycling.

4.4. Robustness of the meta-analysis

Despite the authors' efforts to address methodological and data inconsistencies among LCA studies, many factors may influence the results of the meta-analysis. To examine the robustness of the meta-analysis, we have tested the influence of foreground and inventory data, EoL modelling approaches, and LCIA methods on the outcomes of the meta-analysis. The results of robustness test indicate that, when the full harmonization method was applied, variations in the selected foreground and inventory data and LCIA methods do not significantly affect the meta-analysis results. However, it is not surprising that different EoL modelling approaches have a significant impact on the outcomes. This is because various EoL modelling methods can greatly influence the environmental impacts of different EoL treatments. Previous studies have noted that the 100:0 approach does not allocate environmental benefits to the existing system (Wang et al., 2023; Yang et al., 2024). As a result, the environmental loads of recycling and reuse are often similar to their opposing treatments due to the lack of recognized benefits. In contrast, the 0:100 approach allocates the environmental benefits of recycling and reuse to the existing system, making their environmental performance significantly better than that of the opposing treatments. The 50:50 approach allocates half of the impact of recycling or reuse to the existing system, resulting in environmental benefits that are lower than those in the 0:100 approach but higher than in the 100:0 approach. Both the 100:0 and 50:50 approaches tend to diminish the environmental benefits of recycling and reuse compared to the 0:100 method. Therefore, it is suggested that the 0:100 approach is more suitable for assessing the environmental impacts of building reuse and recycling, as it clearly allocates the environmental benefits associated with reuse and recycling.

4.5. *Contributions, limitations, and future research directions*

Conducting a meta-analysis of the environmental impacts of building reuse and recycling is challenging due to the existing limitations of existing LCA studies. The lack of transparency in LCA methodologies, such as ill-defined inventory data, makes it difficult for researchers to replicate, reproduce, or verify findings, ultimately undermining the reliability of individual LCA studies and meta-analyses. To facilitate a meta-analysis, this study has to make several assumptions to harmonize the methodologies of individual studies. Additionally, it examines the influence of foreground and inventory data, EoL modelling approaches, and LCIA methods on the meta-analysis results to enhance the robustness of the outcomes. This study makes a methodological contribution by guiding future researchers in conducting similar meta-analyses, taking into account the heterogeneity of individual LCA studies and its impact on the meta-analysis outcomes. Furthermore, the study provides a practical contribution by offering empirical evidence to practitioners and policymakers for promoting timber and DfD structures and enhancing the reusability of concrete, steel, and timber materials. This reinforces the recommendations made by Minunno et al. (2021).

Despite these efforts, this study has several limitations. First, this meta-analysis focused solely on the environmental indicator GWP, as this was the primary indicator considered in the selected LCA studies. While GWP provides valuable insights into climate change, it overlooks other environmental impacts associated with building reuse and recycling processes, such as energy consumption, which has been addressed in previous meta-analyses (e.g., Minunno et al., 2021; Peng et al., 2022). Relying on a single indicator makes it challenging to capture interactions between environmental indicators, as strategies aimed at reducing carbon emissions may exacerbate other environmental issues. This narrow focus could lead to incomplete conclusions about the environmental sustainability of circular economy practices in the building sector. Second, the system boundaries in this study exclude the operational stage. This exclusion is due to the fact that most of the selected LCA studies did not consider this stage. As a result, the study may overlook the environmental impact during the operation stage, leading to an incomprehensive interpretation of the meta-analysis. Moreover, only static LCA studies were included in the meta-analysis. The omission of dynamic LCA studies may limit the ability to examine the effects of temporal and spatial variations on the meta-analysis outcomes. Notably, most selected papers on building reuse and recycling are static LCA studies, which constrains the scope of this meta-analysis. Finally, excluding non-English literature may introduce bias by omitting valuable non-English LCA studies, potentially limiting the generalizability of the findings across different geographical contexts.

This paper has discovered several limitations of previous LCA studies, which may influence the quality of the meta-analysis. To facilitate a replicable meta-analysis of the environmental benefits of building reuse and recycling in the future, it is recommended that future LCA studies should 1) collect and publish detailed inventory data, including localized characterization factors, material grades, transportation mode and distance, and geographic locations; 2) consider the entire life cycle of building products or construction materials from cradle to cradle; and 3) assess a range of environmental indicators including operational emissions and energy consumptions.

5. Conclusion

It is widely acknowledged that, from an environmental perspective, reuse is preferable to recycling, and recycling is preferable to landfilling. However, this conclusion is based on individual LCA studies that utilize various methodologies and address different building types. To better understand the environmental benefits of reuse and recycling, this study makes the first attempt to conduct a meta-analysis of building LCA studies, focusing on both partially and fully harmonized methodologies. The partial harmonization process emphasizes aligning functional units, impact allocation methods, system boundaries, and upstream processes. Building on this, the full harmonization process further aligned inventory data and LCIA methods. This study offers a methodological contribution by helping future researchers conduct similar meta-analyses while considering the variability among individual LCA studies and its effect on the results. This effort addresses the limitations of previous studies that have not thoroughly examined how different LCA methodologies influence the outcomes of meta-analysis.

One of the key findings indicates that the environmental impact of the recycling scenario (a combination of recycling and landfilling) is 61.1 % of landfilling with the partial harmonization method and 73.5 % of landfilling with the full harmonization method. Similarly, the environmental impact of reuse scenarios (a combination of reuse, recycling, and landfilling) is 58.2 % of recycling scenarios with the partial harmonization method, and 62.9 % of recycling scenarios with the full harmonization method. The novelty of the results lies in its quantitative comparison of environmental impacts across various EoL strategies and identifying the potential of environmental impact reduction between EoL strategies. Also, these results provide strong evidence that the full harmonization method may underestimate environmental benefits.

This paper clarifies that while recycling is generally more environmentally beneficial than landfilling, the environmental benefits of recycling concrete compared to landfilling are less significant than those of recycling steel and timber. Additionally, changes in the recycling rate of concrete demonstrate less sensitivity to output variations than those of steel and timber. Given the relatively small environmental benefits of recycling concrete, future efforts should focus on improving recycling technologies to enable the upcycling of concrete products rather than downcycling.

The study also confirms the environmental benefits of building reuse compared to recycling. These benefits are particularly significant in mass timber and DfD modular buildings, as opposed to conventional steel-framed and concrete structures. Additionally, the reuse rates of concrete, steel, and timber are sensitive to output, indicating that increasing these rates can greatly enhance environmental benefits. Therefore, it is essential to improve the reusability of building components and materials. This paper highlights that reusing mass timber and DfD modular buildings can yield substantial environmental advantages over recycling. Consequently, policymakers should prioritize developing supportive regulations and incentives to encourage the adoption of reusable or DfD designs, while industry professionals should apply DfD principles and mass timber systems to maximize reuse potential and corresponding environmental benefits.

The primary contribution of this paper is to provide reliable results on the environmental benefits of reuse and recycling through a rigorous meta-analysis of building LCA studies. This research presents clear evidence that reuse should be prioritized in the EoL phase of buildings. Additionally, it offers practical recommendations for enhancing building reuse and recycling practices by improving building design and advancing upcycling technologies. The present research methods can be replicated by further studies to minimize research bias when more individual LCA studies on various building types and materials are conducted while offering transparent information about LCA methodologies.

CRediT authorship contribution statement

Bowen Zheng: Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Yang Yang:** Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Albert Ping-chuen Chan:** Writing – review & editing, Supervision, Funding acquisition. **Hao Jiang:** Writing – review & editing, Supervision, Project administration. **Zhikang Bao:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146149.

Appendix A

Table A1
Overview of representative review studies on circular economy in the built environment

Author (Year)	Journal	Methodology	Topic	Typical keywords
Benachio et al. (2020)	J. Clean. Prod.	Systematic literature review, quantitative and qualitative	Circular economy in the construction industry	Circular economy, building, reuse, case, technique
Chen et al. (2022)	J. Clean. Prod.	Systematic literature review, qualitative	Construction supply chain	Reuse, recycle, recovery, building, house, circular, end-of-life
Hossain and Ng (2018)	J. Clean. Prod.	Systematic literature review, qualitative	Building environmental impact assessment	Lifecycle assessment, carbon emission, building, circular economy, greenhouse gas emission, environmental impact
Illankoon and Vithanage (2023)	J. Build. Eng.	Systematic literature review, qualitative	Circular economy in the construction industry	Circular economy, circular, construction, building, built environment
Larsen et al. (2022)	J. Build. Eng.	Literature review, qualitative,	Building sustainability assessment	Life cycle assessment, life cycle sustainability assessment, circular, building, built environment
Lei et al. (2021)	J. Build. Eng.	Literature review, qualitative	Building sustainability assessment	Circular economy, life cycle assessment, built environment
Lima et al. (2024)	Renew. Sust. Energ. Rev.	Literature review, qualitative	Circular economy practices for building materials	Circular economy, demolition reuse, recycling, manufacturing
Minunno et al. (2021)	Renew. Sust. Energ. Rev.	Systematic literature review, Meta-analysis	Building sustainability assessment	Life cycle assessment, LCA, embodied energy, carbon emissions, building
Muñoz et al. (2023)	Sustain. Prod. Consum.	Systematic literature review, qualitative	Circular economy in the construction industry	Circular economy, construction, building, life cycle, environment
Rakhshan et al. (2020)	Waste Manag. Res.	Systematic literature review, quantitative and qualitative	Reuse practices in the building sector	Building, reuse, recovery, reclaim, waste, salvage
Shooshtarian et al. (2022)	Sustain. Prod. Consum.	Literature review, qualitative	Construction waste management	Construction waste, construction and demolition waste, landfilling, recycling, waste minimisation, technology
Yang et al. (2022)	J. Clean. Prod.	Scientometric review, quantitative	Circular economy in the construction industry	Circular economy, reuse, recycle, cradle to cradle, building

Table A2
Query strings used in Scopus and Web of Science

Scopus:
TITLE-ABS-KEY(("building*" OR "House*" OR "Existing building*") AND ("EOL" OR "End-of-Life" OR "End of Life" OR "EoL") AND ((("reus*" OR "reutiliz*" OR "repurpos*" OR "upcycl*") AND ("recycl*" OR "recovery" OR "closed-loop" OR "downcycl*")) OR (("recycl*" OR "recovery" OR "closed-loop" OR "downcycl*") AND ("landfill" OR "disposal" OR "dumping")) OR ("circular" OR "circular economy" OR "linear")) AND ("life cycle assessment" OR "LCA" OR "life cycle" OR "lifecycle" OR "Global Warming Potential" OR "GWP" OR "GHG" OR "greenhouse gas" OR "CO2" OR "carbon dioxide" OR "carbon emission*" OR "environmental impact") AND ("scenario*" OR "compar*"))
Web of Science:
TS=(("building*" OR "House*" OR "Existing building*") AND ("EOL" OR "End-of-Life" OR "End of Life" OR "EoL") AND ((("reus*" OR "reutiliz*" OR "repurpos*" OR "upcycl*") AND ("recycl*" OR "recovery" OR "closed-loop" OR "downcycl*"))

(*continued on next page*)

Table A2 (*continued*)

Scopus:
OR (("recycl*" OR "recovery" OR "closed-loop" OR "downcycl*") AND ("landfill" OR "disposal" OR "dumping")) OR ("circular" OR "circular economy" OR "linear")) AND ("life cycle assessment" OR "LCA" OR "life cycle" OR "lifecycle" OR "Global Warming Potential" OR "GWP" OR "GHG" OR "greenhouse gas" OR "CO2" OR "carbon dioxide" OR "carbon emission*" OR "environmental impact") AND ("scenario*" OR "compar*"))

Table A3
Summary of the basic information of shortlisted comparative LCA studies.

Case	Building type	Studies	Region	Cycle time	Module	Functional unit
1	Timber house	Passarelli and Mouton (2023)	United States	Single	A B C D	m^2
2	Timber house	Tanthanawiwat et al. (2024)	Thailand	Single	A C D	m^2
3	Concrete house	Proietti et al. (2013)	Italy	Single	A B C D	m^2/year
4	Concrete house	Tanthanawiwat et al. (2024)	Thailand	Single	A C D	m^2
5	Mass timber building	Darby et al. (2013)	British	Single	A C D	Whole building
6	Mass timber building	Greene et al. (2023)	United States	Single	A C D	m^2
7	DfD modular building	Minunno et al. (2020)	Australia	Multiple	A B C D	Whole building
8	DfD modular building	Jayawardana et al. (2023)	Sri Lanka	Single	A C D	Modular unit
9	DfD building	Eberhardt et al. (2019)	Danish	Multiple	A B C D	m^2
10	Steel frame building	Vares et al. (2018)	Finland	Multiple	A B C D	m^2
11	Steel frame building	Vares et al. (2020)	Finland	Multiple	A B C D	m^2
12	Steel frame building	Lei et al. (2023b)	China	Single	C D	m^2
13	Concrete building	Blengini (2009)	Italy	Single	A B C D	m^2
14	Concrete building	Wang et al. (2018)	China	Single	C D	Whole building
15	Concrete building	Tulevech et al. (2018)	Thailand	Single	A B C D	m^2/year
16	Concrete building	Kröhnert et al. (2022)	Switzerland	Single	A B C D	Whole building
17	Concrete building	Keena et al. (2023)	Canada	Single	A B C D	m^2
18	Concrete building	Keena et al. (2023)	Peru	Single	A B C D	m^2
19	Concrete building	Lei et al. (2023a)	China	Single	C D	m^2
20	Concrete building	Lei et al. (2023b)	China	Single	C D	m^2
21	Concrete building	Wang et al. (2024)	China	Single	C D	Whole building

Data availability

Data will be made available on request.

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