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Critical Reviews

A Systematic Review on Life Cycle Assessment of Prefabricated Buildings

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A R T I C L E I N F O

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A B S T R A C T

The construction sector has a significant impact on the environment, highlighting the need for sustainable building practices to decrease the emissions and propose alternative construction solutions. In this framework, prefabricated construction methods offer a promising solution, providing benefits such as reduced material waste, improved energy efficiency, and alignment with net-zero principles. The Life Cycle Assessment (LCA) approach represents a key tool for evaluating the environmental performance of buildings throughout their entire life cycle, enabling a direct comparison between prefabricated and traditional construction methods. This systematic review examines the application of LCA methodologies to assess the environmental impacts of modular and prefabricated buildings. By analysing recent peer-reviewed articles, this study investigates the use of key LCA elements, including software, databases, System Boundaries, Functional Unit, and environmental impact categories. The impact categories analysis indicates that, in terms of global warming potential, 1 m^2 of structure impacts an average of 325, 327, and 389 kg CO_2 eq for steel, wood, and concrete, respectively, for phases A and C. Furthermore, this review highlights and discusses the main limitations and the research gaps of the current studies of LCA methodology applied to modular construction, emphasising the need to intervene on five potential improvement areas: (i) methodological development, (ii) policy implications, (iii) stakeholder engagement and awareness, (iv) digital tools and innovation and (v) Circular Economy (CE) integration.

Abbreviations

BIM	Building Information Modelling
CE	Circular Economy
EoL	End-of-life
FD	Fossil Depletion
FE	Freshwater Eutrophication
FSS	Fossil Resource Scarcity
FU	Functional Unit
FW	Freshwater Ecotoxicity
GHG	Greenhouse Gas
GW	Global Warming Potential
HC	Human Carcinogenic Toxicity
HN	Human Non-carcinogenic Toxicity
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment method
LU	Land Use
ME	Marine Eutrophication
MR	Mineral Resource Scarcity
MX	Marine Ecotoxicity
OD	Stratospheric Ozone Depletion
PCR	Product Category Rules
PE	Primary Energy
PM	Fine Particulate Matter Formation
SB	System Boundaries
SCM	Supplementary Cementitious Materials
SL	Reference Service Life
TA	Terrestrial Acidification
TE	Terrestrial Ecotoxicity
WC	Water Consumption

1. Introduction

The global pursuit of environmental sustainability is increasingly influencing all sectors of human activity, with particular attention being given to the construction industry (Bakindi et al., 2025; Myint and

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Shafique, 2024; Olsson et al., 2024). Clear articulation of sectoral challenges strengthens the framing of sustainability discussions (Saleh et al., 2024a). The construction sector accounts for a significant portion of global energy consumption, Greenhouse Gas (GHG) emissions, and material resource depletion, thereby playing a pivotal role in the broader conversation around climate change and sustainability (Almusaed et al., 2024; Bonoli et al., 2021; Myint et al., 2025). Globally, in 2019, buildings were responsible for approximately 12 Gigatons CO_2 eq of GHG emissions (UNEP, 2024). Of this, about 24% resulted from on-site fuel use, 57% from off-site electricity and heat generation, and 18% was embodied in materials and construction (UNEP, 2024). By 2022, global emissions from the sector were just under 10 Gigatons CO_2 eq, representing 37% of global carbon dioxide emissions for that year (UNEP, 2024). In the EU, emissions from buildings decreased by 34% from 2005 to 2022, with a further slight decline in 2023 (EEA, 2024). However, the construction sector accounted for 34% of EU energy-related emissions in 2022 (EEA, 2024). To reduce its impacts, the industry must focus on strategies such as selecting optimal construction methods, utilising sustainable materials, and improving energy efficiency throughout the building life cycle (Araújo et al., 2020; Mirabella et al., 2018; Roopesh et al., 2024). By implementing these changes, the construction industry can significantly contribute to global efforts to create a more sustainable future (Fei et al., 2021).

Modular and prefabricated construction methods have increasingly attracted attention as promising strategies to improve the sustainability of the built environment and increase safety against external agents such as radon gas (Baltrocchi et al., 2023b; Choi et al., 2019; Wu et al., 2021). Prefabricated buildings can be made of concrete, steel, wood or different combinations of the three materials (Tavares et al., 2021; Yuan et al., 2018; Zhao, 2014). Prefabricated construction refers to a process in which building components are manufactured off-site under controlled conditions and assembled on-site (Fang et al., 2021; Hussein et al., 2021). This approach offers several potential environmental benefits, including reduced material waste, increased energy efficiency during construction, shorter project timelines, and improved quality control (Dal Lago et al., 2025a; Loizou et al., 2021). Prefabrication also aligns well with concepts such as the Circular Economy (CE), in which materials and components are designed for reuse, repurpose or recycling, further contributing to resource conservation and environmental protection (Garusinghe et al., 2023; Minunno et al., 2018; Zairul, 2021). Modular constructions are usually more sustainable than *cast-in-situ* concrete construction despite employing materials with higher environmental impacts, thanks to the substantial reduction in the volume of materials employed and to the structural optimisation (Dal Lago et al., 2025b; Liang et al., 2020; Sandanayake et al., 2018).

Despite the apparent advantages, the environmental impacts of modular and prefabricated construction are highly dependent on numerous factors, including the types of materials used, manufacturing processes, transportation logistics, building design, and end-of-life (EoL) management (Ghanbari, 2023; Jangam and Myneni, 2025; Lei et al., 2023). Therefore, it becomes critical to systematically assess these impacts using comprehensive and standardised approaches such as Life Cycle Assessment (LCA). According to EN 15978:2001 (CEN, 2011), the issue of sustainable construction should be tackled from a life cycle point of view, computing the environmental impact of all different life stages through proper indicators (Anand and Amor, 2017).

LCA is a standardised approach designed to evaluate the environmental impacts, which follows the guidelines outlined in the standards ISO 14040:2006 and 14044:2006 (ISO, 2006a, 2006b). This methodology provides a comprehensive, system-wide perspective on production processes by objectively assessing and quantifying energy and environmental burdens and potential impacts associated with a product, process, or activity throughout its entire life cycle (Baltrocchi et al., 2025a, 2025c; Romagnoli et al., 2024). This approach spans from the extraction of raw materials through production, distribution, use, and eventual disposal (Baltrocchi et al., 2024; Ferronato et al., 2023). LCA is an essential tool for assessing sustainability and facilitating informed decision-making, as it identifies the environmental impacts in the life cycle, prioritises sustainable alternatives, and develops strategies to minimise the overall environmental burden associated with technologies (Baltrocchi et al., 2025b; Barbhuiya and Das, 2023; Shafique et al., 2022). Furthermore, it can be combined with the Social LCA (SLCA) and Life Cycle Costing (LCC) to assess economic and social aspects (Baltrocchi et al., 2023a; Pryshlakivsky and Searcy, 2021).

In literature, the review of Kamali and Hewage (2016) has only one study that discussed the LCA approach applied to modular buildings. The study revealed that, on average, modular buildings exhibit better environmental performance than conventional buildings throughout their life cycle. The benefits are primarily in terms of energy performance. Other reviews have focused on the environmental sustainability of modular or prefabricated buildings. For instance, Parracho et al. (2025) analysed the state of the integration of digital technologies with modular construction methods, extending the analysis to circular and bioclimatic efforts, renewable energy sources, and passive building design strategies. The study of Jayawardana et al. (2025) investigated the state-of-the-art of economic sustainability and social sustainability of prefabricated construction. Ly et al. (2024) evaluated the CE integrated with modular construction. The research of Boafo et al. (2016) analysed the performance of modular construction considering acoustic constraints, seismic resistance, thermal behaviour, energy consumption, and life cycle analysis based on existing case studies. Marjaba and Chidiac (2016) revised the metrics for sustainability and resiliency for buildings. Further details of the reviews are reported in Table S1.

Existing literature provides substantial insights into various aspects of sustainability in modular and prefabricated buildings, such as integrating digital technologies, CE principles, economic and social sustainability, and specific performance parameters. However, a significant gap remains in comprehensively assessing environmental sustainability through applying the LCA methodology to modular and prefabricated buildings. The only review concerning LCA applied to modular buildings was published in 2016; therefore, a new literature review is needed, also following the latest regulations and standards that incorporate new studies, addressing variations in approaches, methodologies, and outcomes across the entire life cycle of a modular and prefabricated buildings. Our study fills these gaps by critically assessing how prefabricated construction materials, building use, and typical LCA elements (e.g., software, database, Life Cycle Impact Assessment method (LCIA), Functional Unit (FU), Reference Service Life (SL), System Boundaries (SB), and impact categories) are used in existing researches on modular or prefabricated buildings while identifying opportunities for standardisation and methodological improvement to improve the accuracy and comparability of environmental impact assessments in this area.

2. Materials and methods

2.1. Selection strategy

To select proper documents, the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines have been followed (Page et al., 2021). To choose only peer-reviewed documents, the literature review was searched using the Scopus database (Meho and Rogers, 2008; Naoum and Egbu, 2015). Scopus was selected because it offers excellent access to curated abstracts and citation databases linked to various academic literature (de Souza et al., 2024; Falagas et al., 2008; Martín-Martín et al., 2018). The following combinations of search query were used in Scopus and applied to the title, abstract, and keywords: "life AND cycle AND assessment" AND "modular AND buildings" OR "modular AND construction" OR "prefabricated AND construction" OR "precast AND construction". The search returned 423 results spread over a time period between 1994 and April 2025. The flow diagram of literature review is reported in Fig. 1.

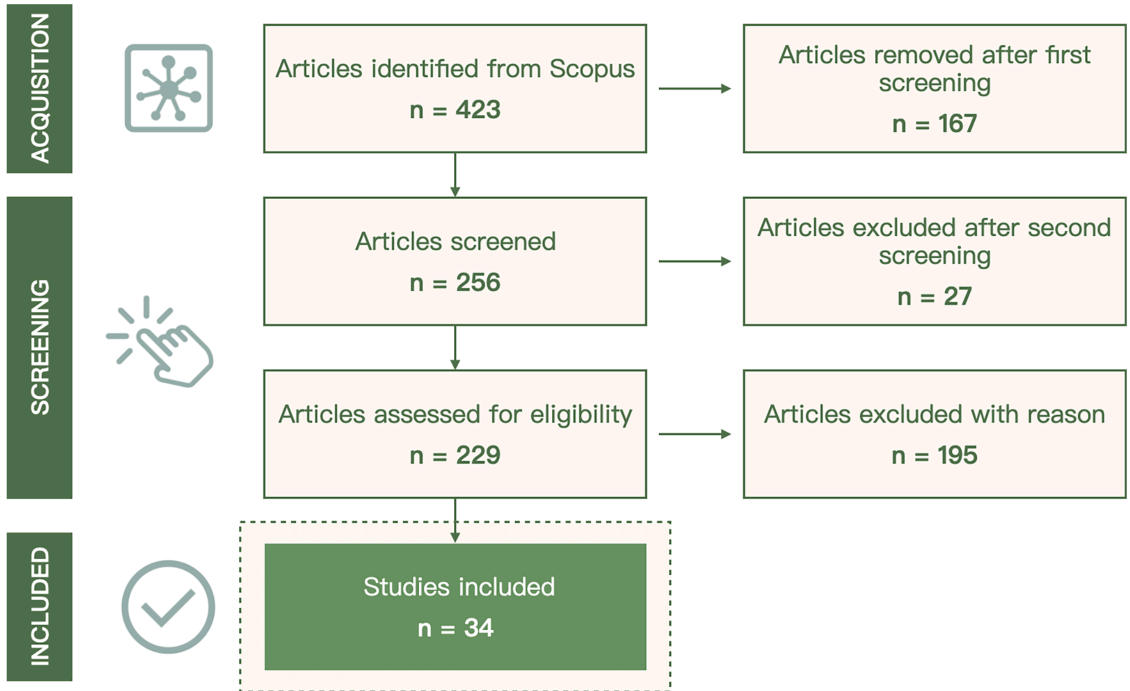

Fig. 1. Flow diagram of literature review (n: number of articles).

2.2. *Initial screening*

In the first screening, only research articles published in international peer-reviewed journals were selected; books, book chapters, conference papers, reviews, and conference reviews were excluded. This is in order to analyse only research articles that have undergone a high-quality peer-review and selection process (Chigbu et al., 2023; Polanin et al., 2019). Then, 167 documents were excluded, and 256 passed the first screening. In the second screening, only research articles published from 2010 to April 2025 in the English language and under the subject areas engineering, environmental science and energy were included in order to focus on the most recent studies and the right subject area. 27 papers are excluded, and 229 articles passed for the final selection.

2.3. *Final selection*

In the final screening, all research articles from the previous phase were examined in detail. In particular, two exclusion criteria were applied: (i) the construction system of the analysed building and (ii) the application of the LCA analysis. In this phase, titles and abstracts of the selected papers were read in order to identify the focus of the works. In addition, the following keywords were searched in the body text: "modular", "prefabricated", "precasting" for the first criterion, while "LCA" and "Life Cycle Assessment" for the second criterion. On the one hand, according to the first exclusion criterion, all articles that did not have modular and prefabricated buildings as their primary focus were discarded. On the other hand, regarding the second criterion, all studies that did not apply the LCA methodology or used the LCA analysis only partially to assess environmental impacts were excluded. Finally, according to the selected criteria, 34 research articles were identified as relevant and were included in the final revisions. However, it is necessary to highlight that it cannot be excluded that other peer-reviewed documents fitting the criteria of the screenings can be available in different databases.

3. Results

3.1. *General overview of selected articles*

3.1.1. *Years of publications and locations of the studies*

From 2010 to 2018, the number of publications remained very low, no more than one per year, excluding three at 2015 (Balasbaneh and Bin Marsono, 2017; Bonamente and Cotana, 2015; Cao et al., 2015; Dong et al., 2015; Monahan and Powell, 2011; Quale et al., 2012). However, starting in 2019, it is notable a rise in the number of articles. The number of publications reached its peak in 2024, with 6 articles, the highest of the considered period of 15 years (Al-Sammar and Aleisa, 2024; Gao et al., 2024; Souaid et al., 2024; Wen et al., 2024; Yang et al., 2024). The trend of publications over the years is reported in Fig. 2a. Most of the studies are concentrated in a few key countries, with Hong Kong and China leading with 5 publications each (Cai et al., 2023; Cao et al., 2015; Dong et al., 2015; Gao et al., 2024; Satola et al., 2020; Teng and Pan, 2019; Tian and Spatari, 2022; Wen et al., 2024; Yang et al., 2024; Zheng et al., 2025). Other significant contributors include Canada and Malaysia, with 3 studies each (Balasbaneh and Bin Marsono, 2017; Balasbaneh and Ramli, 2020; Balasbaneh and Sher, 2021; Dara et al., 2019; Head et al., 2020; Kamali et al., 2019). Europe provided 12 articles across 10 countries (Andersen et al., 2022; Arslan et al., 2023; Bonamente and Cotana, 2015; de Paula Filho et al., 2024; Iuorio et al., 2019; Manso et al., 2018; Monahan and Powell, 2011; Shokouhi and Weidlich, 2025; Souaid et al., 2024; Szalay et al., 2022; Tavares and Freire, 2022; Wang and Sinha, 2021). The map of global distribution is shown in Fig. 2b.

3.1.2. *Regionals gaps*

The regional distribution of publications indicates a concentration in East Asia, particularly China and Hong Kong, with several studies originating from these regions. This prevalence is primarily due to rapid urbanisation and high housing demand, which have driven the adoption and evaluation of modular and prefabricated systems. In contrast, Europe and North America have smaller contributions, reflecting more mature construction markets and lower immediate housing pressure.

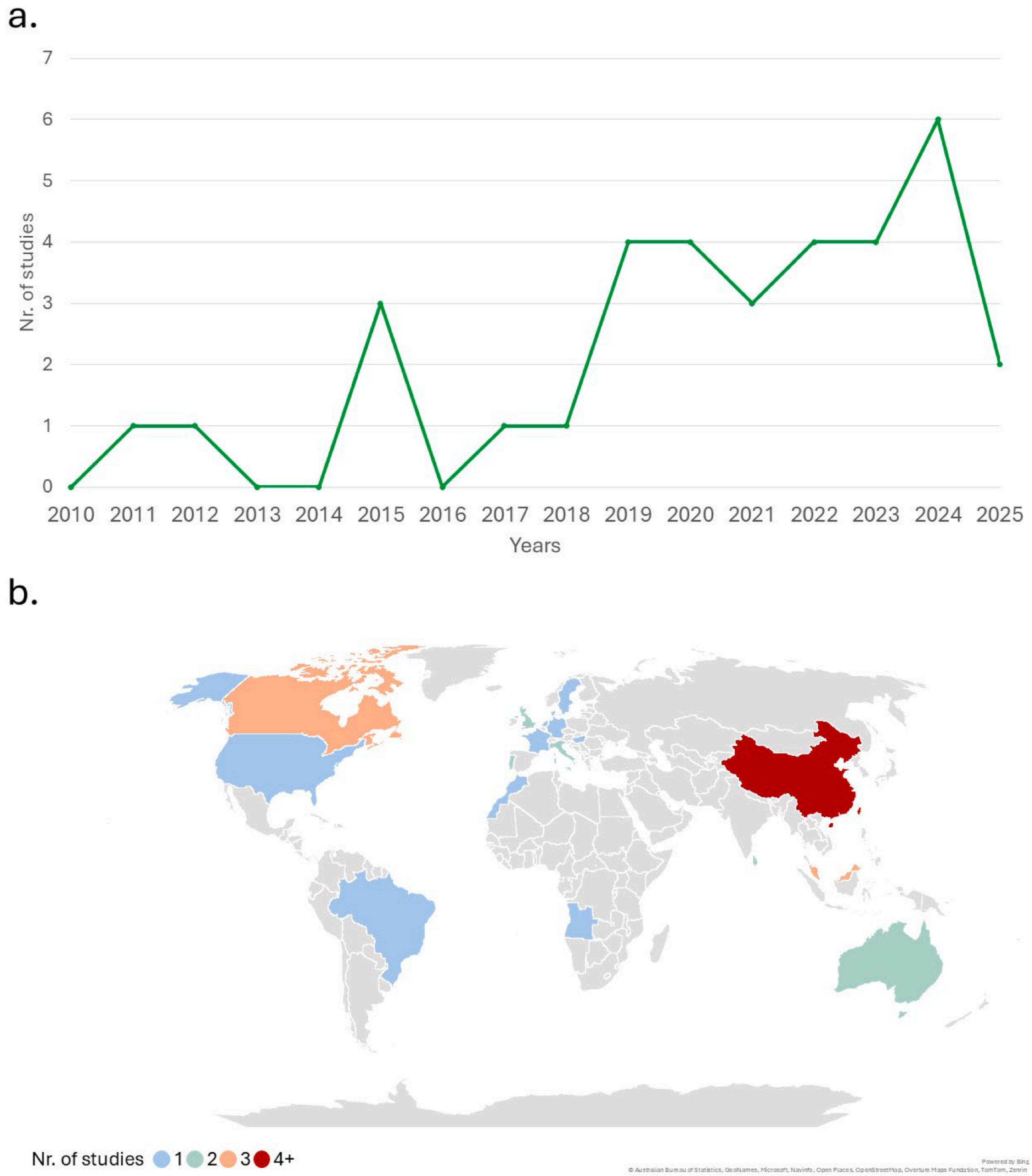

Fig. 2. General overview of selected articles: (a.) trend of publications over the years and (b.) global distribution map.

3.1.3. Main modular construction materials, building types, aims of the studies and main findings

The studies considered in this review were classified according to (i) the main prefabricated construction material, which means that which constitutes the largest volume of the structural body material of the building (concrete, steel, wood or fiberglass); (ii) the final use of the building (residential or commercial); (iii) aims of the LCA analysis. On the one hand, regarding the main material, 16 articles focus on concrete, followed by 15 studies on steel, 8 on wood, 1 on fiberglass, and 1 not declared the material. On the other hand, 27 studies considered residential buildings, while 7 articles evaluated commercial constructions, including offices, industrial buildings, and schools. The third category can be divided into three subcategories according to their aims: (i) comparison of prefabricated construction with *cast-in-situ* buildings, (ii) evaluation in order to support the decision-making process and (iii) environmental impacts analysis of the case studies. The contributions are equally distributed among the three subcategories: 12 studies have the objective of supporting the decision-makers, 12 other papers evaluate the environmental impacts of case studies, and 10 publications compare prefabricated buildings with traditional solutions.

The main findings show that prefabricated constructions generally have lower environmental impacts than traditional construction methods. In particular, the wooden buildings consistently show the lowest environmental impact, followed by steel structures, especially when including EoL stages (Balasbaneh and Bin Marsono, 2017; Cai et al., 2023; Kamali et al., 2019; Minunno et al., 2020; Quale et al., 2012; Satola et al., 2020). However, considerable variability across studies is evident. Wooden buildings often emerge as the lowest-impact option, but this result depends on methodological choices. For instance, studies that account the stage B or assume shorter SL for the wood elements tend to report higher emissions, thus reducing the relative advantage of the wood. In contrast, when longer SL assumption are incorporated or stage

B is omitted, wood buildings consistently achieve favourable performance. As regarding the steel structures, generally show intermediate performance, but the results are primarily influenced by assumptions regarding recycling rates and burden allocation in EoL stages. Prefabricated concrete buildings, while varying in performance across regions, generally achieve significant emission reductions due to prefabrication, which allows for optimised use of concrete (Andersen et al., 2022; Arslan et al., 2023; Balasbaneh and Sher, 2021; Cao et al., 2015; Dong et al., 2015; Jayawardana et al., 2023a; Tian and Spatari, 2022; Wang and Sinha, 2021). This variability highlights that comparative results are highly sensitive to SB, SL assumptions, and EoL stages, highlighting the need for transparency and harmonisation in LCA methodologies to ensure robust comparisons between construction methods. The general overview of the selected studies is reported in Table 1.

3.2. LCA methodology features

3.2.1. Software, database and life cycle impact assessment methods (LCIA)

The LCA methodology features are shown in Table 2. The LCA software Simapro (Goedkoop et al., 2016) was used by 16 articles, followed by GaBi (Spatari et al., 2001) with 3 studies and Athena (Holzinger et al., 2014) with 2 articles. Again, eBalance (Bai et al., 2017), eFootprint (Lao et al., 2023), Hawking/Brown Emission Reduction Tool (HBERT) (Bowles et al., 2021), OpenLCA (Pamu et al., 2022) and Tool to Optimise the Total Environmental impact of Materials (TOTEM) (Jurgelionis et al., 2013) are used by 1 study each. Moreover, 8 works do not declare which software they used to perform the LCA analysis.

Regarding the Life Cycle Inventory (LCI) database, 23 articles take background data from Ecoinvent (Frischknecht et al., 2005) in different versions; this represents the majority of the studies. The others are definitely less used: 2 contributes each involve Athena (Holzinger et al., 2014) and Ökobaudat (Gantner et al., 2018) databases, while eFootprint (Lao et al., 2023), GaBi (Spatari et al., 2001) and Inventory of Carbon and Energy database (ICE) (Abdelaal et al., 2023) are performed by 1 article each. Industry Data 2.0 (Grajewski et al., 2024) and Malaysia Life Cycle Inventory Database (MY-LCID) (Hafizan et al., 2021) are used in 2 works, each within Ecoinvent. Again, two studies involved the Environmental Product Declaration (EPD) (Del Borghi, 2013) for background data of the analysis, while 3 articles do not declare the LCI database.

The evaluation of the environmental impacts is carried out using 11 different LCIA methodologies. The most used method is ReCiPe (Goedkoop et al., 2009) with 8 studies, followed by CML 2001 (Gabathuler, 2006) and IPCC (Roscoe, 2016) with 3 contributes, EN 15804+A2 (Van Gulck et al., 2022) with 2 articles and BEES (Lippiatt, 2002), CML I-A (Gabathuler, 2006), GHGProtocol (Hickmann, 2017), ILCD 2011 (Chomkhamsri et al., 2011), IMPACT 2002+ (Jolliet et al., 2003), TRACI (Bare, 2011) and USLCI (Deru, 2009) with 1 study each. However, 10 studies do not report the LCIA methods involved in the LCA analysis.

3.2.2. Functional unit and reference service life

The majority of the studies defined their Functional Unit (FU) as 1 building unit and 1 m^2, with 14 and 12 articles, respectively. The FU of 1 building unit refers to all FUs that include the entire building in different dimension, while 1 m^2 includes all FUs that considers the surface of the building or the construction site. Other FUs are 1 m^3 evaluated in 5 studies and 1 m^2/year, 1 ft^2 and 2,000 ft^2 for 1 paper each. As regards the Reference Service Life (SL), 50 years is the most used time with 18 studies, followed by 60 years with 4 articles, 30 with 2 papers, while 25 and 10 years are considered in 1 study each. SL is not declared in 8 contributions. Finally, 1 article considered the SL of 15, 25, 50 and 100 years.

3.2.3. System boundaries and life cycle stage

According to Product Category Rules (PCR) for construction materials (EPD International AB, 2023) and EN 15804 (EN, 2012), in this study, the considered System Boundaries (SB) to classify the selected articles are divided into four main life cycle stages: A, B, C and D (out of the SB). A1–A3 (Production stage) is subdivided into (i) the A1 phase, which considers the extraction and processing of all raw materials and energy (ii) the A2 phase, which accounts for the transport of the raw materials to the manufacturing site (iii) A3 phase that includes all activities related to manufacturing within the facility site. A4–A5 (Construction stage) is divided into (i) A4 module that includes transport from the manufacturing facility to the building site and (ii) A5 module that reports the installation of prefabricated elements into the buildings. B1–B7 (Operational stage) includes (i) B1 stage that considers any emissions to the environment of the used product and technical operations on the product, (ii) B2 stage that represents the maintenance, (iii) B3 module the repair, (iv) B4 stage reports the replacement, (v) B5 module the refurbishment, (vi) B6 stage the operational energy use and (vii) B7 stage the operational water use. C1–C4 (EoL stage) includes (i) the C1 module that represents the de-construction or dismantling of the entire building, (ii) the C2 stage that includes the transport to waste disposal site, usually 50 km are assumed, (iii) C3 stage that considers waste processing for reuse, recovery, and/or recycling and (iv) C4 module that models final disposal. D (Benefits of recovery stage) declares the environmental benefits of reusable products, recyclable materials, or energy recovery. This module is outside the SB; therefore, the environmental loads do not add to the impacts of other phases. Fig. 3 reports the reference SB considered in this study according to EN 15804.

As regards the results of the analysis, the entire SB plus D phase is analysed in 5 studies (in B stage 1 study only considered B1 and B2, 1 study excluded B5, and 1 study excluded B2; in C stage 1 study excluded B2 and 1 study only included C1 and C2). 8 articles considered from A to C modules (in B stage 1 study included only B4 and B6; in C stage 1 study excluded C1). The SB from A to B stages are analysed only in 1 study, while only A modules are included in 9 contributions (1 study included only A4). The modules A, C and D are considered in 5 studies (1 study includes only C1 and C2; 1 study includes only A5, C1 and C4). A and C stages are included in 3 articles, while 1 work is focused only on A1, C1, C3, C4 and D modules. Finally, 1 contribution includes only the C phase. In summary, 33 studies include A1–A3 modules (1 study only included A1); 32 works analyse A4–A5 stages (1 study excluded A4, 1 study only included A5 and 1 study only included A4); 15 contributions study B modules (1 study only included B2 and B4, 1 study only included B4 and B6, 1 study excluded B5, 1 study excluded B2 and 1 study only included B2); 16 articles include C phases (1 study only included C1, C3 and C4, 1 study excluded C1, 1 study only included C1 and C2, 1 study only included C1 and C2, 1 study only included C1 and C4); 12 works aim with D module.

3.2.4. Environmental impact categories

The relevant environmental impact categories are chosen according to ReCiPe (Goedkoop et al., 2009) as the most used LCIA method in selected studies (Feng et al., 2023). In particular, 16 impact categories are analysed. All 34 studies report the results in terms of Global Warming Potential (GW). Other relevant impact categories are Freshwater Eutrophication (FE) with 14 works, followed by Terrestrial Acidification (TA) with 13 studies. 12 contributions each are included in Primary Energy (PE) and Terrestrial Ecotoxicity (TE). Again, Fossil Depletion (FD) and Marine Eutrophication (ME) were selected in 11 studies each, while Stratospheric Ozone Depletion (OD) and Fine Particulate Matter Formation (PM) were in 10 articles each. 7 studies include Human Carcinogenic Toxicity (HC), 6 contributions analyse Freshwater Ecotoxicity (FW), Land Use (LU) and Marine Ecotoxicity (MX), 5 studies select Mineral Resource Scarcity (MR), 3 articles study Water Consumption (WC) and 1 work chooses Human Non-carcinogenic Toxicity (CN). In summary, 14 articles consider only the environmental

Table 1
General overview of selected articles: years of publications, location of the studies, main construction material, building type, aims of the contributions and main findings.

Ref.	Year	Location	Main material	Building use	LCA study aims	Key findings
Zheng et al. (2025)	2025	Hong Kong	Steel	Residential	Assess the reuse and recycling potential of modular units and their elements from an environmental perspective. Improve the data collection and storage process across multiple use cycles. Provide a solution for visualising modular building systems' reuse and recycling potential.	Reusing and recycling the modular elements offset a portion of the environmental impact, resulting in equivalent carbon dioxide emissions. In the first use cycle, the building emits 830 tons of CO_2 eq per unit. Intermediate use cycle(s) 350 ± 124 tons CO_2 eq per unit. Last use cycle 770 ± 93 tons CO_2 eq per unit.
Shokouhi and Weidlich (2025)	2025	Germany	n.a.	Commercial	Evaluate the environmental impacts of office buildings in different shapes (12 × 14 square meter modular units) and heights (3.6 and 12 m).	The emissions ranged from 42.14 to 74.08 kg CO_2 eq/m^2 NFA*a, depending on building shape and height (NFA: Net Floor Area).
de Paula Filho et al. (2024)	2024	Luxembourg	Concrete, steel and wood	Commercial	Compare the impact of structural design choices on the overall GW of an office building made in concrete, steel or wood. Investigate the influence of critical assumptions, such as EoL scenarios for wood.	Concrete buildings emit 235 kg CO_2 eq/m^2, followed by structural steel buildings with 170 kg CO_2 eq/m^2 and other steel buildings with 125 kg CO_2 eq/m^2. The emissions of wood construction ranged from 169 to 226 kg CO_2 eq/$m^{2,}$ depending on the EoL treatment.
Yang et al. (2024)	2024	Hong Kong	Steel	Commercial	Assess the environmental credits and loads associated with reusing modular components over multiple use cycles.	The reuse and recycling of the modular unit resulted in approximately 9,007 ± 362 kg CO_2 eq per unit, 2,925 ± 602 kg CO_2 eq per unit, and 8,433 ± 544 kg CO_2 eq per unit in the first, intermediate, and last use cycles, respectively.
Souaid et al. (2024)	2024	Netherlands	Wood	Residential	Evaluate the impact of downsizing and the use of wood on the embodied carbon of a new-build dwelling.	Emissions ranged from 42,608 to 70,384 kg CO_2 eq per unit for the wood designs versus 54,681 to 91,270 kg CO_2 eq per unit for their concrete counterparts.
Al-Sammar and Aleisa (2024)	2024	Kuwait	Fiberglass	Residential	Assess the environmental implications of constructing a fiberglass modular prefabricated room compared to a conventional concrete structure.	The energy requirements significantly contribute to the impact of climate change, accounting for 77% and 90% of concrete and fiberglass modules, respectively. Fiberglass modules exhibit substantially higher environmental impacts compared to concrete modules in agricultural land occupation (143%), terrestrial ecotoxicity (81%), and urban land occupation (66%).
Gao et al. (2024)	2024	China	Concrete	Residential	Analyse and calculate the spatial distribution of GHG emissions from prefabricated components and buildings during China's production, transportation, and construction stages.	The selection of prefabricated construction can lead to a 32% reduction in total GHG emissions per square meter, with 269.16 kg CO_2 eq/m^2 emissions, compared to traditional construction with 393.63 kg CO_2 eq/m^2 emissions.
Wen et al. (2024)	2024	Hong Kong	Steel	Residential	Estimate the EoL carbon emissions and savings potential, focusing on the steel-framed modular residential building.	Net carbon emissions during the EoL stage could be saved −764.40 kg CO_2 eq /m^2. An average of 41.56 kg CO_2 eq/m^2 is still released in the EoL stage, most of which is contributed by transportation, waste disposal, demolition, and waste processing.
Jayawardana et al. (2023b)	2023	Sri Lanka	Steel	Commercial	Conduct a design-stage life cycle assessment of a design for disassembly and linear versions of a modular building unit to evaluate the potential environmental benefits.	The overall impact of the design for the disassembly version is 472.36 kg CO_2 eq per unit compared to 1,285.09 kg CO_2 eq per unit by linear unit.
Cai et al. (2023)	2023	China	Steel	Residential	Analyse the life cycle GHG emission characteristics of prefabricated light-steel buildings compared to the traditional cast-in-place buildings. Explore their GHG emission in order to evaluate the reduction potentials.	The results show that the life cycle GHG emissions of prefabricated light-steel buildings and traditional cast-in-place buildings are 2,848.58 and 3,055.11 kg CO_2 eq/m^2, respectively.
Jayawardana et al. (2023a)	2023	Sri Lanka	Concrete	Commercial	Investigation of the cradle-to-gate environmental performance of prefabricated construction methods compared to traditional *in-situ* construction in buildings.	Results showed that buildings with prefabricated components provide environmental impact savings. The prefabricated buildings emitted 258.86 kg CO_2 eq/m^2.
Arslan et al. (2023)	2023	United Kingdom	Concrete	Residential	Establish environmental impacts from prefabricated residential buildings against the current benchmarking in the UK.	The emissions of the prefabricated building were 1,076 kg CO_2 eq/m^2. The impact was low compared to the business-as-usual model.

(*continued on next page*)

Table 1 (*continued*)

Ref.	Year	Location	Main material	Building use	LCA study aims	Key findings
Tavares and Freire (2022)	2022	Angola, Brazil, France, Morocco and Portugal.	Steel	Residential	Assess the environmental impacts of a lightweight prefabricated house for seven house locations.	The comparison reported that the average impacts ranged from 560 to 672 kg CO_2 eq per unit for the embodied stage and 860 to 2,890 kg CO_2 eq per unit for the operational stage.
Tian and Spatari (2022)	2022	China	Concrete	Residential	Evaluate and compare the environmental impacts of prefabricated and traditional building construction in China.	The traditional building emitted 363.59 kg CO_2 eq/m^2, while the prefabricated project emitted 324.86 kg CO_2 eq/m^2, an approximate 11% reduction. Building materials contributed most to GHG emissions in both projects, making up 92% and 92% in traditional and prefabricated projects, respectively.
Szalay et al. (2022)	2022	Hungary	Wood	Residential	Explore whether carbon neutrality can be achieved over the whole life cycle of a building with a net balance approach.	The assessment showed that the ratio of embodied and operational impacts is typically 1:2 for wooden buildings and 1:1.5 for brick buildings. In both cases, life cycle carbon neutrality could be achieved with additional photovoltaic panels installed on the roof.
Andersen et al. (2022)	2022	Australia and Denmark	Concrete	Residential	Evaluate and compare the environmental impacts of conventional and modular housing by applying "absolute environmental sustainability" measures.	In general, modular buildings presented lower environmental impacts across all impact categories. The primary contributor was the operational phase.
Balasbaneh and Sher (2021)	2021	Malaysia	Concrete	Residential	Assess three construction techniques: on-site concrete, Individual Panel System and Prefabricated Prefinished Volumetric Construction.	The production and construction stage of the on-site concrete had emissions of 49,800 kg CO_2 eq per unit, followed by Individual Panel System with 44,500 kg CO_2 eq per unit and Prefabricated Prefinished Volumetric Construction with 40,900 kg CO_2 eq per unit.
Kucukvar et al. (2021)	2021	Qatar	Concrete and steel	Commercial	Quantify the endpoint impact categories for a sustainable modular stadium design of the RAA Stadium in Qatar.	The planned circularity allowed for savings of more than 4.26E07 species.year compared with 1.7 species.year across the overall life-cycle impacts in the EoL phase.
Wang and Sinha (2021)	2021	Sweden	Concrete	Residential	Compare the environmental performance of the prefabricated building with different prefabricated rates from a life cycle perspective. Examines whether the increasing prefabricated rate is more environmentally friendly.	The total emissions of reference prefabricated buildings are 185.8 kg CO_2 eq/m^2. The changing emissions rate, depending on the scenario, ranged from around −3% to 9%.
Minunno et al. (2020)	2020	Australia	Steel	Residential	Evaluate the environmental impact of a modular building following the CE design principles for disassembly and reuse. Compare it to the same modular building constructed without considering the disassembly phase.	The prefabricated building emitted 47.2 tons CO_2 eq per unit from the A to C phases. Regarding stage D, the emissions are −5.4 tons CO_2 eq per unit.
Satola et al. (2020)	2020	China	Steel	Residential	Assess the environmental impacts from the baseline, low-energy, net-zero energy development, and off-grid energy designs.	The total impacts are equal to 209.5 tons CO_2 eq per building area for the baseline design, followed by low energy design with 151.6 tons CO_2 eq per building area, off-grid design with 51.2 tons CO_2 eq per building area and net-zero with 30.3 tons CO_2 eq per building area.
Head et al. (2020)	2020	Canada	Wood	Residential	Calculate the climate change impacts of wood building products for different use contexts across Canada.	The climate change impacts range from −1,264 to −388 kg CO_2 eq/m^3 for the wood product cases, affected mainly by wood product lifespans.
Balasbaneh and Ramli (2020)	2020	Malaysia	Concrete and steel	Residential	Compare the environmental impacts of steel and concrete prefabricated prefinished volumetric construction life cycle.	The steel structure had more emissions of 9,623.13 kg CO_2 eq per unit than the concrete building (8,264.03 kg CO_2 eq per unit).
Teng and Pan (2019)	2019	Hong Kong	Concrete	Residential	Evaluate the environmental impacts of concrete prefabricated buildings.	The average cradle-to-end of construction embodied emissions are 0.561 kg CO_2 eq/m^2.
Dara et al. (2019)	2019	Canada	Concrete and wood	Residential	Evaluate the integrated life cycle impact of a modular container-based single-family house compared to a conventional lightwood house.	The most impactful solution is the lightwood code with 3,629 tons CO_2 eq per unit, followed by the container code with 3,533 tons CO_2 eq per unit, improved lightwood with 1,346 tons CO_2 eq per unit and improved container with 1,322 tons CO_2 eq per unit.
Iuorio et al. (2019)	2019	Italy	Steel	Residential	Investigate the environmental impacts of lightweight steel systems.	The total impact of the lightweight steel systems is 8,710 kg CO_2 eq per unit.

(*continued on next page*)

Table 1 (*continued*)

Ref.	Year	Location	Main material	Building use	LCA study aims	Key findings
Kamali et al. (2019)	2019	Canada	Wood	Residential	Analyse the environmental impacts of single-family buildings constructed by traditional on-site and wood modular off-site construction methods.	The wood modular constructions have an average emissions of 476 kg CO_2 eq/ft^2. This value is lower than that of the traditional construction method emissions.
Manso et al. (2018)	2018	Portugal	Steel	Residential	Identify the environmental impacts throughout the life cycle of a steel modular building.	The total emissions of the modular building are 138.71 kg CO_2 eq/m^2.
Balasbaneh and Bin Marsono (2017)	2017	Malaysia	Concrete, steel and wood	Residential	Compare the environmental impacts of six different types of buildings: Block-work system, precast concrete framing, steel framework system, timber prefabricated, glued laminated wood and steel with timber wall, laminated veneer lumber, and steel with timber wall.	The most impactful solution is a block-work system with 30,600 kg CO_2 eq per unit, followed by a steel frame work system with 23,800 kg CO_2 eq per unit, precast concrete framing with 11,900 kg CO_2 eq per unit, glued laminated timber and steel with timber wall with 6,020 kg CO_2 eq per unit, laminated veneer lumber and steel with timber wall with 5,800 kg CO_2 eq per unit and timber prefabricated 2,040 with kg CO_2 eq per unit.
Bonamente and Cotana (2015)	2015	Italy	Concrete and steel	Commercial	Assess the environmental performance of different typologies of industrial prefabricated buildings.	The average emissions of the four selected buildings are 133.7 kg CO_2 eq/m^3 (33.95 kg CO_2 eq/m^{3,} not considering the use phase).
Dong et al. (2015)	2015	Hong Kong	Concrete	Residential	Investigate the carbon emissions of concrete precast and cast-*in-situ* construction methods for high-rise residential buildings.	The emissions of the precast construction are 692 kg CO_2 eq /m^3. The precasting solution can lead to a 10% carbon reduction compared to *cast-in-situ* building.
Cao et al. (2015)	2015	China	Concrete	Residential	Evaluate prefabricated buildings' environmental benefits and limitations in the Chinese residential building industry.	The prefabricated buildings emit a total of 193 kg CO_2 eq/m^2, which is around 10% higher than traditional buildings.
Quale et al. (2012)	2012	United States	Wood	Residential	Quantify the environmental impacts of constructing a typical residential home using the two methods based on data from several modular construction companies and conventional home builders.	The average total emissions of the modular building are equal to 13,600 kg CO_2 eq per 2,000 sq ft home.
Monahan and Powell (2011)	2011	United Kingdom	Wood	Residential	Quantify the embodied carbon in constructing a wood building and compare the model with traditional construction methods.	The building's emissions are 405 kg CO_2 eq/ m^2. Comparison with traditional construction methods resulted in a 34% reduction in embodied carbon.

Notes: *n.a.: not available.*

impacts of GW.

3.2.5. *LCA results: focus on global warming potential (GW)*

The only impact category taken into consideration by all the selected studies is GW. For this reason, in this paragraph, the main results in terms of GW for the construction materials and for the FUs equal to 1 m^2 and 1 building unit are reported. Starting with the prefabricated concrete buildings, the emissions per 1 m^2 are shown to span from 139 to 764 kg CO_2 eq (average 357 kg CO_2 eq) in stage A, 280 kg CO_2 eq in stage B and 32 in stage B kg CO_2 eq (Arslan et al., 2023; Cao et al., 2015; de Paula Filho et al., 2024; Dong et al., 2015; Gao et al., 2024; Jayawardana et al., 2023a; Manso et al., 2018; Teng and Pan, 2019; Tian and Spatari, 2022; Wang and Sinha, 2021). Considering the FU equal to 1 building unit, the emissions ranged from 616 to 49,360 kg CO_2 eq (average 22,924 kg CO_2 eq) in phase A, from 124 to 1,875 kg CO_2 eq (average 736 kg CO_2 eq) in phase B and from 935 to 2,490 kg CO_2 eq (average 1,712 kg CO_2 eq) in phase C (Balasbaneh and Ramli, 2020; Balasbaneh and Sher, 2021; Monahan and Powell, 2011; Tavares and Freire, 2022). One study reports the results per 1 m^3, which are 37 kg CO_2 eq, 100 kg CO_2 eq and −2 kg CO_2 eq per A, B, and C phases, respectively (Bonamente and Cotana, 2015). Regarding 1 m^2 of prefabricated buildings composed of steel, the stage A has emissions of 440 kg CO_2 eq, stage B 2,680 kg CO_2 eq and stage C ranged from −242 and 42 kg CO_2 eq (average −115 kg CO_2 eq) (Cai et al., 2023; Wen et al., 2024). The GW per 1 unit of steel buildings is ranged from 8,409 to 15, 182 kg CO_2 eq in the case of module A (average 22,798 kg CO_2 eq), from 55 to 4,100 kg CO_2 eq for module C (average 2,385 kg CO_2 eq) and from −39,400 to −6,824 kg CO_2 eq in module D (average −23,773 kg CO_2 eq) (Iuorio et al., 2019; Jayawardana et al., 2023a; Minunno et al., 2020; Yang et al., 2024). The buildings made in wood report impacts for FU of 1 m^2 equal to 68 kg CO_2 eq, 184 kg CO_2 eq and 259 kg CO_2 eq for A, B, and C stages, respectively (Souaid et al., 2024). Furthermore, the FU of 1 building unit composed of wood had emissions ranging from 4,125 to 56,000 kg CO_2 eq for stage A (average 30,063 kg CO_2 eq), from 440 to 2, 398,000 kg CO_2 eq for stage B (average 1,199,220 kg CO_2 eq) and from 1,265 to 3,000 kg CO_2 eq for stage C (average 2,132 kg CO_2 eq) (Balasbaneh and Bin Marsono, 2017; Dara et al., 2019; Szalay et al., 2022). The summary of the comparison of the results between concrete, steel and wood is reported in Fig. S1.

4. Discussion

4.1. *Considerations about the results*

The results of this systematic review demonstrate that the adoption of modular and prefabricated construction methods generally offer environmental benefits compared to traditional building practices. Many of the studies analysed indicated prefabrication as beneficial in reducing the consumption of raw materials. Given that the production of raw materials is the primary driver of environmental impacts, using prefabricated structures improves the environmental performance of buildings, especially in terms of GW, which aligns with global efforts for

Table 2
LCA methodology features: software, database, Life Cycle impact assessment methods (LCIA), Functional Unit (FU), System Boundaries phases and Impact categories.

Ref.	Software	Database	LCIA	FU	SB stages					SL [yr]	Impact categories															
					A1–A3	A4–A5	B	C	D		GW	PE	OD	PM	TA	FE	ME	TE	FW	MX	HC	HN	LU	MR	FD	WC
Zheng et al. (2025)	n.a.	Ecoinvent and Industry Data 2.0	n.a.	Modular building	x	x		x	x	50	√															
Shokouhi and Weidlich (2025)	Gabi	Ökobaudat	n.a.	1 m^2/ NFA*a	x	x		x		50	√															
de Paula Filho et al. (2024)	n.a.	EPDs	EN 15804	1 m^2	x	x		x	x	50	√															
Yang et al. (2024)	n.a.	Ecoinvent and Industry Data 2.0	n.a.	Modular unit	x	x		x	x	50	√															
Souaid et al. (2024)	TOTEM tool	Ecoinvent	n.a.	m^2 for plane surfaces, m for structural elements and individual piece for other elements.	x	x	x[1]	x	x	60	√															
Al-Sammar and Aleisa (2024)	n.a.	Ecoinvent	ReCiPe	Single module with a floor area of 18 m^2	x	x				25	√		√	√	√	√	√	√	√	√	√		√	√	√	
Gao et al. (2024)	eFootprint	eFootprint	n.a.	1 m^3 of prefabricated components	x	x		x		n.a.	√															
Wen et al. (2024)	SimaPro	n.a.	n.a.	1 m^2 of the building area				x		50	√															
Jayawardana et al. (2023b)	SimaPro	Ecoinvent	IPCC and ReCiPe	Modular building unit	x[2]			x[3]	x	10	√			√	√	√		√	√	√	√		√	√	√	
Cai et al. (2023)	eBalance	Ecoinvent	CML 2001	1 m^2 of building area	x	x	x	x		50	√															
Jayawardana et al. (2023a)	SimaPro	Ecoinvent	IPCC /ReCiPe	1 m^2 of the construction floor area	x	x				n.a.	√			√	√	√	√			√					√	
Arslan et al. (2023)	HBERT	ICE and EPDs	n.a.	1 m^2 of a build-up	x	x	x	x	x	60	√															
Tavares and Freire (2022)	SimaPro	Ecoinvent	CML 2001	Lightweight prefabricated house with 56 m^2 of gross floor area	x	x	x			50[4]	√	√	√		√	√	√	√						√		
Tian and Spatari (2022)	Gabi	Ecoinvent	ReCiPe	1 m^2 of the construction area	x	x				n.a.	√	√		√	√	√	√	√								
Szalay et al. (2022)	n.a.	Ökobaudat	CML 2001	Full compact house	x	x	x[5]	x[6]		30	√															
Andersen et al. (2022)	OpenLCA	Ecoinvent	ILCD 2011	Habitable floor area of a single-family home	x	x	x[7]	x	x	50	√		√			√	√									
Balasbaneh and Sher (2021)	SimaPro	MY-LCID and Ecoinvent	ReCiPe	1 m^2 of the total floor area of buildings	x	x		x[8]	x	50	√		√					√			√				√	
Kucukvar et al. (2021)	n.a.	Ecoinvent	ReCiPe	Entire stadium area of 450,000 m^2	x	x	x	x		30	√				√	√		√	√	√			√			
Wang and Sinha (2021)	SimaPro	Ecoinvent	ReCiPe	1 m^2 of floor area	x	x				50	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Minunno et al. (2020)	SimaPro	Ecoinvent	CML-IA	Whole building	x[9]	x	x[10]	x	x	n.a.	√	√			√	√	√	√							√	
Satola et al. (2020)	SimaPro	Ecoinvent	ReCiPe	Total gross building area	x	x	x	x		25	√	√	√	√	√	√									√	√
Head et al. (2020)	n.a.	Ecoinvent	IPCC	1 m^3 of wood product used in buildings or construction projects	x	x		x		15, 25, 50 and 100	√															
Balasbaneh and Ramli (2020)	SimaPro	MY-LCID and Ecoinvent	IMPACT 2002+	1 m^2 of a wall component	x	x	x[11]	x[12]	x	50	√	√		√									√		√	
Teng and Pan (2019)	SimaPro	n.a.	n.a.	1 m^2 and 1 m^3	x	x		x		50	√															
Dara et al. (2019)	Athena	Athena	TRACI	House with a gross floor area of 238 m^2	x	x	x	x		50	√	√	√	√	√	√	√	√							√	
Iuorio et al. (2019)	SimaPro	Ecoinvent and EPDs	EN 15804	25 m^2 and 1 m^2	x	x[13]		x[14]	x	50	√	√	√	√		√	√	√								
Kamali et al. (2019)	Athena	Athena	TRACI	1 ft^2 of average-quality single-family buildings	x	x[15]				60	√	√	√	√	√	√	√	√							√	
Manso et al. (2018)	GaBi	GaBi	CML 2001	1 m^2 of each material required to assemble the Geogreen System	x	x	x			50	√								√		√					
Balasbaneh and Bin Marsono (2017)	Simapro	MY-LCID and Ecoinvent	IPCC	Building with 1 m^2 of living area	x	x	x	x		50	√															

(*continued on next page*)

Table 2 (*continued*)

Ref.	Software	Database	LCIA	FU	SB stages					SL [yr]	Impact categories															
					A1–A3	A4–A5	B	C	D		GW	PE	OD	PM	TA	FE	ME	TE	FW	MX	HC	HN	LU	MR	FD	WC
Bonamente and Cotana (2015)	Simapro	Ecoinvent	n.a.	1 m^3 of prefabricated building	x	x	x	x		50	√	√														
Dong et al. (2015)	Simapro	Ecoinvent	GHGProtocol	1 m^3 of concrete	x	x	x	x		n.a.	√															
Cao et al. (2015)	n.a.	n.a.	n.a.	1 m^2	x	x				50	√	√	√	√	√	√	√	√	√	√	√		√	√	√	√
Quale et al. (2012)	Simapro	Ecoinvent	BEES	2,000 ft^2	x	x		x		n.a.	√															
Monahan and Powell (2011)	Simapro	Ecoinvent	USLCI	House with a total foot print area of 45 m^2 and a total internal volume of 220.5 m^3	x	x				n.a.	√	√														

Notes: n.a.: not available;
[1] only included B2 and B4.
[2] only included A1.
[3] only included C1, C3 and C4.
[4] average.
[5] only included B4 and B6.
[6] excluded C1.
[7] excluded B5.
[8] only included C1 and C2.
[9] excluded A4.
[10] excluded B2.
[11] only included B2.
[12] only included C1 and C2.
[13] only included A5.
[14] only included C1 and C4.
[15] only included A4.

System Boundaries phases description: A1–A3: Production stage; A4–A5: Construction stage; B: Use stage; C: End-of-life stage; D: Benefits of recovery.

Acronyms of impact categories: GW: Global Warming Potential; PE: Primary Energy; OD: Stratospheric Ozone Depletion; PM: Fine Particulate Matter Formation; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TE: Terrestrial Ecotoxicity; FW: Freshwater Ecotoxicity; MX: Marine Ecotoxicity; HC: Human Carcinogenic Toxicity; HN: Human Non-carcinogenic Toxicity; LU: Land Use; MR: Mineral Resource Scarcity; FD: Fossil Depletion; WC: Water Consumption.

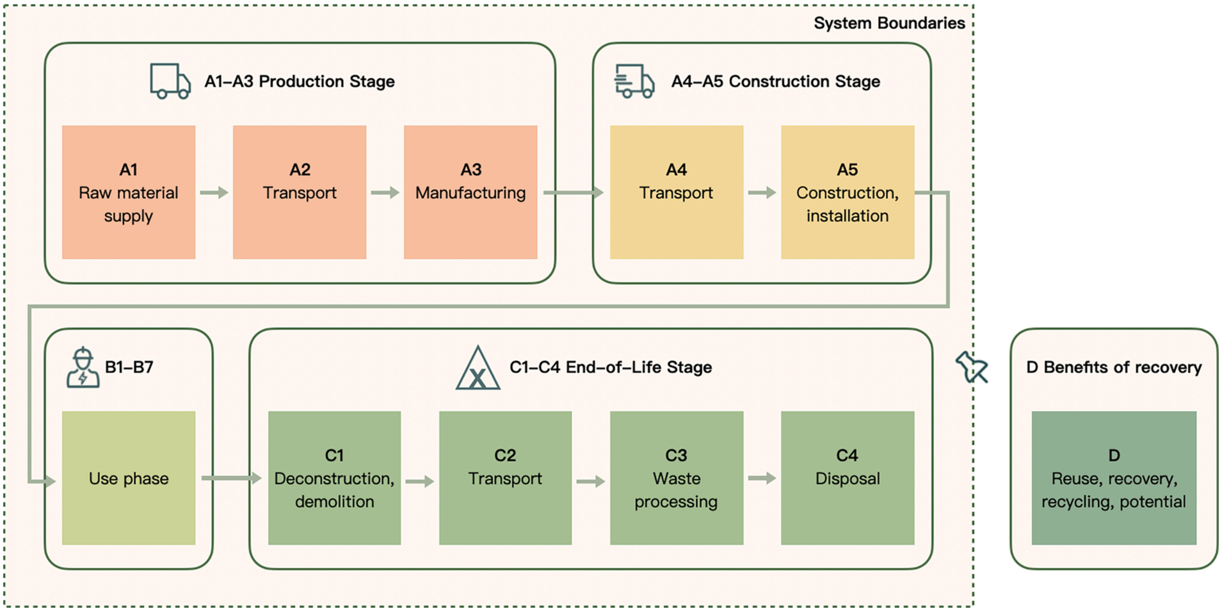

Fig. 3. Reference System Boundaries and Life Cycle stages considered in the review analysis.

sustainability and net zero emissions targets (Mehra et al., 2022; Ryłko-Polak et al., 2022).

As regarding the regionals gaps, the prevalence of studies in China and Hong Kong can be explained by the combined effect of high population density, rapid urban expansion, and governmental support for industrialised construction methods, which create strong incentives for research and practice in prefabrication. By contrast, Europe and North America show fewer studies, as their more established construction markets face lower urgency in adopting new building paradigms. This imbalance highlights a regional gap that may limit the global applicability of current findings, underlining the need to foster research in underrepresented regions.

The findings consistently highlight wood as the most sustainable material in module A, considering the FU of 1 m^2 (average 68 kg CO_2 eq/m^2), followed by concrete (average 357 kg CO_2 eq/m^2) and steel (average 440 kg CO_2 eq/m^2). In contrast, steel presents the lower impacts in stage C (average −115 kg CO_2 eq/m^2), followed by concrete (average 32 kg CO_2 eq/m^2) and wood (average 259 kg CO_2 eq/m^2) (Arslan et al., 2023; Cai et al., 2023; Cao et al., 2015; de Paula Filho et al., 2024; Dong et al., 2015; Gao et al., 2024; Jayawardana et al., 2023a; Manso et al., 2018; Souaid et al., 2024; Teng and Pan, 2019; Tian and Spatari, 2022; Wang and Sinha, 2021; Wen et al., 2024). This is due to the almost total recyclability of the steel (Broadbent, 2016; Qin and Kaewunruen, 2022). The optimised use of raw materials, the reduction of waste and the recyclability of modular construction, according to Sbahieh et al. (2025), contribute significantly to its lower environmental impact. The constant improvements in GW observed for concrete structures reflect the progress in material optimisation and prefabrication processes. However, the variability in the environmental performance of concrete compared to other materials, such as wood, highlights the importance of locally sourced materials, transport logistics and EoL strategies (Chamasemani et al., 2023). Several studies have investigated alternatives to mitigate the environmental impacts of cement. For example, Caldas et al. (2021) proposed Portland cement replacement with fly ash and metakaolin as Supplementary Cementitious Materials (SCM) and workable wood bio-concretes, while Mistri et al. (2021) evaluated the environmental implications of the use of bio-cement treated recycled aggregate in concrete.

Modular steel construction has shown interesting potential for GW reduction, primarily due to its recyclability and lightweight (Hasanbeigi et al., 2014; He and Wang, 2017). However, as also reported in the study of La Rosa et al. (2025), the transportation and the high energy used in steel production stages can accentuate its environmental impact. Chen et al. (2022) evaluated the recent global research regarding minimising the carbon emissions of steel building products. The most frequent studies included the recovery of furnace gas and waste heat, alternative fuels and energy alternative/improved ironmaking technologies.

The analysis of environmental impacts across different materials reveals significant variability among studies, highlighting the sensitivity of environmental assessments to methodological choices. Wood buildings are often shown as the lowest-impact option; however, these results are strongly influenced by assumptions regarding SL and the inclusion of stage B. Studies incorporating shorter SL or including stage B tend to show higher emissions, thus reducing the relative environmental advantage of wood. In contrast, when assuming longer SLs or excluding stage B, wood consistently achieves favourable performance. Steel structures generally exhibit intermediate environmental performance; however, results are highly dependent on assumptions regarding recycling rates and burden sharing across EoL phases. These observations underscore the importance of carefully considering methodological parameters when comparing building materials, as even slight variations can significantly impact conclusions.

4.2. LCA method key observations

The review identified substantial variations in the LCA methodologies employed, highlighting significant methodological discrepancies that could impact the reliability and comparability of the results (Wu and Su, 2020). ReCiPe emerged as the most commonly applied LCIA method; however, many studies did not explicitly state their LCIA methodology. This lack of transparency hinders comparisons between studies and limits the use of different impact categories to assess modular constructions. The selected studies used 9 different databases, further conditioning the comparability of the results.

Furthermore, the diversity of FU and SL years used in the reviewed articles highlights that the studies follow several standards. Among all the FU approaches, the building unit is the most used. However, since each building unit has different characteristics, using this FU has implications for interpreting the results and a broader applicability. The same problem is evident in SL, as the variability across years does not allow proper comparison, especially in the operational phases (stage B) and EoL scenarios (stage C).

Similarly, SB varied across studies, with many studies omitting operational phases (stage B) or EoL benefits (stage D). This selective approach risks underestimating or misrepresenting life cycle impacts. Studies that incorporated full SB according to EN 15804 (modules A to D) provided clearer information on the full life cycle impacts of modular buildings, highlighting their holistic environmental benefits as discussed in Durão et al. (2020).

Regarding the impact categories, all selected studies evaluated GW, while less than half evaluated other impact categories. This shows that, although there is great sensitivity towards CO_2 emissions, other important parameters such as water consumption and fossil depletion that would allow us to have a clear idea of the complete environmental profile are not considered. Analysing the major impact categories is essential to understand the real impacts on human health, ecosystems and resources (Feng et al., 2023).

Scientific journals and databases should adopt more rigorous reporting standards, making the declaration of the FU, SB, SL, and the LCIA method mandatory to ensure transparency and comparability between research papers and reports.

4.3. Research gaps and improvement areas

After having extensively discussed the results of this review, this section aims to summarise the current research gaps and the areas in which improvement can be made in assessing the environmental impacts of prefabricated and modular buildings through LCA methodology. In particular, as reported in Fig. 4, five areas have been identified: (i) methodological development, (ii) policy implications, (iii) stakeholders engagement and awareness, (iv) digital tools and innovation and (v) Circular Economy (CE) integration.

4.4. Methodological development

As previously reported, significant diversity in LCA methodologies regarding SB, FU, and SL has been observed. This lack of uniformity hinders the comparability of results between different researchers. Future studies should follow the existing standards, such as EN 15804, more rigorously, including the operational phases (stage B) and end-of-life impacts (stage C), and take into account the complete life cycle phases (modules A-D).

The selected studies should also adopt a standard line for assessing impact categories. Although several papers have evaluated the environmental impacts through the ReCiPe method, most studies prioritise GW over other relevant impact categories, such as water consumption, fossil depletion and terrestrial ecotoxicity. This prevents a holistic understanding of environmental impacts. Practitioners, designers, and researchers should move towards a common standardisation that aligns with the principles of LCA. These are essential components to assess the environmental impact of modular and prefabricated buildings fully. Also, the research of Ali et al. (2025) demonstrates originality by applying decision-making frameworks to underexplored infrastructure contexts, underscoring the importance of methodological innovation in sustainability research.

4.5. Policy implications

Although in recent years, there has been an important political effort towards the principles of environmental sustainability of buildings, this is still insufficient to reach the net zero target by 2050, according to the studies of Ohene et al. (2023, 2022a, 2022b). Current building standards do not sufficiently integrate LCA-based criteria. Politics should encourage using common standards for conducting LCA analysis, especially in modules representing the operational phase (stage B) and the EoL (stage C). Politics should also support the spread of widely recognised certifications, such as EPDs and other environmental certifications (Saleh et al., 2024b). These are drawn up through rigid schemes contained in PCRs and allow comparability across different products (Moré et al., 2022).

Another factor affecting the consistency of the reviewed studies is the role of local regulations. In fact, in Europe, the EN 15804 standard allows for comparisons between studies, as it provides a clear modular structure (A1–A5, B, C, D) and harmonised standards for EPDs. In contrast, Chinese frameworks such as the Green Building Evaluation Standard (GB/T 50,378–2019) (He et al., 2024) and Hong Kong's BEAM Plus (Yeung et al., 2022) primarily promote general sustainability and life cycle awareness, but lack the detailed breakdown of life cycle phases offered by EN 15804. Consequently, studies conducted under these frameworks often differ in how they define system boundaries, limiting their comparability both within Asia and with European research.

Furthermore, it is necessary to encourage the studies to introduce

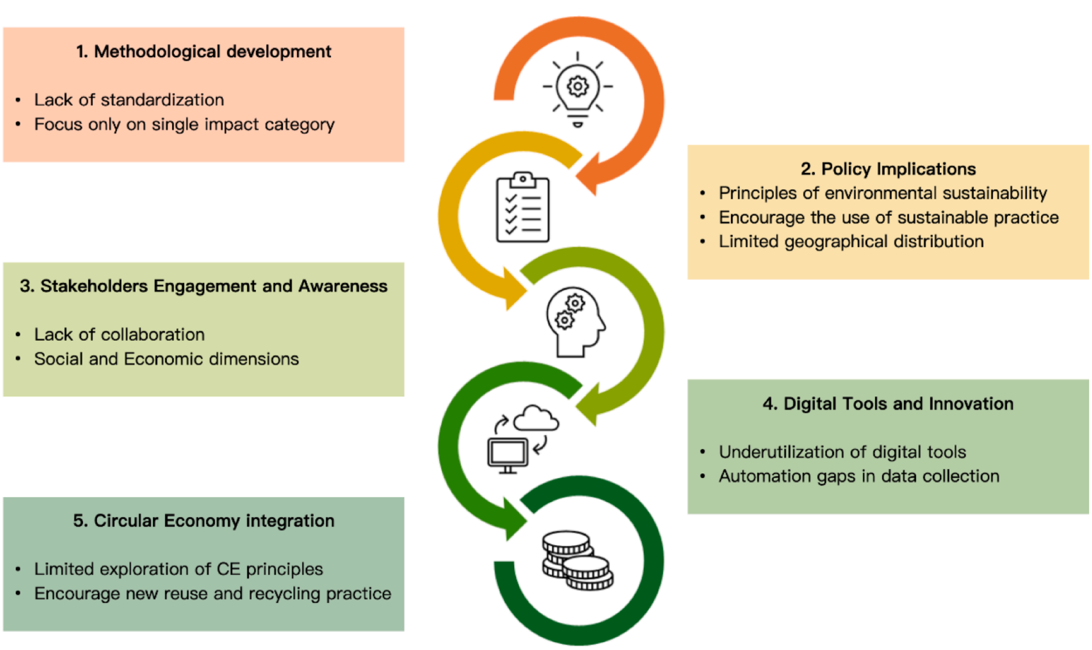

Fig. 4. Closed loop of research gaps and potential improvement areas.

innovative raw materials and new production technologies to decrease the environmental impacts (Uddin et al., 2025). These aspects have also been highlighted in the study by Olumo and Haas (2024). Another significant point from this analysis is the limited geographical distribution of the studies, mainly concentrated in developed regions such as East Asia and Europe. Politics should also encourage the study of modular buildings in developing countries. This geographical disparity limits the development of inclusive policies globally, especially in developing countries, where modular buildings could be proposed as a sustainable solution with affordable costs, according to the research of Ali et al. (2023).

4.6. Stakeholders engagement and awareness

Collaboration between different stakeholders is essential to achieve the common goal of environmental sustainability. However, there is a lack of emphasis on collaboration between stakeholders: too little attention is paid to interdisciplinary cooperation between engineers, environmental scientists, manufacturers and policymakers to address the systemic challenges of modular construction. Manufacturers should provide more primary data without demonstrating low CO_2 emissions for commercial purposes. There should no longer be competition between companies for the lowest GW value. Furthermore, manufacturers should support, as well as policy, the study and development of sustainable raw materials and new technologies to mitigate current environmental impacts.

Stakeholders should also encourage the assessment of social and economic dimensions: most studies ignore social and economic evaluations. A complete sustainability assessment would require integrating LCA with Social LCA (SLCA) and Life Cycle Costing (LCC) analysis (Baltrocchi et al., 2023a). This would allow for a holistic evaluation of the three pillars of sustainability: environmental, economic, and social (Purvis et al., 2019).

4.7. Digital tools and innovation

The review indicated that studies rarely exploit digital tools such as Building Information Modelling (BIM) to improve data collection and integrate environmental analysis. For example, Zheng et al. (2025) studied the integration of BIM with LCA for the reuse and recycling phases of modular steel buildings. Failure to use digital tools represents a limitation since these tools can improve the quality of data collection and process modelling. Again, the review of Tam et al. (2022) Click or tap here to enter text.indicated that, although LCA data sources are well-represented in the study literature, BIM data accessibility remains limited, data exchange is predominantly manual, environmental impacts are mostly visualised through traditional charts, and the majority of studies focus on comparing design alternatives. (Safari and Azar-iJafari, 2021) reported that studies using BIM-LCA primarily base their approaches on manual or semi-automated methods in the early design stages, with limited attention to design variants, incomplete automation of data exchange, and significant opportunities for integrating local databases, sensitivity analyses, and uncertainty assessment frameworks. Furthermore, the study of (Hollberg et al., 2020) shows that the GW assessed during the design phase via BIM is initially overestimated, approximately double that of the final building, which indicates that BIM-based assessments in the early stages can be misleading and highlights the need to improve BIM-LCA integration. On balance, the lack of automation in data collection is also a fundamental problem. LCA studies are often based on fragmented and non-automatic data sources, provided mainly by the manufacturers that influence data accuracy, reproducibility and precision. An improved digital framework could solve this problem. In addition, current standards do not imply integrating LCA analysis with digital tools; therefore, the standards and guidelines must be adequate.

4.8. Circular economy (CE) integration

The modular construction technique aligns with the principles of CE in the building sector. However, further efforts are needed. The current research cannot fully quantify the benefits of reuse, recycling and recovery of material in modular and prefabricated systems. The absence of robust modelling for the life cycle of reuse, recycling and recovery of the components limits the ability to carefully evaluate these systems' long-term sustainability. Several studies have assessed the importance of addressing the principles of the CE in prefabricated and modular buildings. For instance, Senaratne et al. (2025) proposed strategies for integrating sustainable principles into the modular construction industry, aligning with global sustainability benchmarks and advancing a CE. Again, Yang et al. (2024) evaluated the environmental benefits of using modular building components from a multi-use cycle perspective. From here emerges the need to encourage new reuse and recycling practices in line with the most modern principles of the CE.

5. Conclusions

This systematic literature review evaluates the application of LCA analysis to modular and prefabricated buildings. In total, 34 studies were selected that met two main criteria: (i) the construction system of the analysed building must be modular or prefabricated and (ii) the application of the LCA analysis. This study highlights both the environmental benefits of modular construction and the limitations of current research practices. Key findings include:

- Environmental performance: prefabricated construction generally exhibits a lower environmental impact than traditional construction methods, particularly in terms of GW. The optimised material use, waste reduction, and recyclability contribute significantly to this advantage.
- Specific material impacts: wood has the lowest environmental impact in stage A, but higher impacts in the EoL stage (C). Steel exhibits intermediate impacts in the production stages, but benefits from high recyclability. The impacts of concrete vary greatly, influenced by local sourcing, transport logistics, and the use of additional cementitious materials.
- Regional gaps: most studies are concentrated in China and Hong Kong due to their high urban density and government support, while Europe and North America are underrepresented, which limits the global applicability of the results.
- The main methodological limitation of LCA are in (i) FU, which is often defined as a building unit, thereby reducing comparability across studies; (ii) operational phases (Stage B) and end-of-life scenarios (Stage C) are frequently omitted, and (iii) the assessment primarily focuses on GW, with limited consideration of other environmental indicators. Moreover, the use of databases, SB and SL assumptions, and LCIA methods is often inconsistent across studies.

To fill these research and methodological gaps, five potential areas for improvement have been identified:

- Methodological development: adoption of standard frameworks (e.g., EN 15804), including all life cycle phases, and assessment of several indicators.
- Policy implications: stronger integration of LCA-based criteria in building standards, promotion of EPDs, support for innovative materials, and encouragement of prefabricated building studies in developing regions.
- Stakeholders engagement and awareness: greater interdisciplinary collaboration, transparency of primary data, integration of social and economic dimensions (SLCA and LCC) with LCA.

- Digital tools and innovation: wider adoption of BIM-LCA integration for accurate and automated environmental assessment, especially during design and planning stages.
- Circular Economy (CE) integration: enhanced modelling of material reuse, recycling, and recovery to quantify long-term sustainability benefits of prefabricated construction.

Future research and stakeholders involved, such as policymakers, manufacturers and researchers, should consider the improvement areas identified in this review to optimise modular construction practices globally and further their contribution to sustainable development.

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Data availability

All data generated or analysed during this study are included in this published article.

CRediT authorship contribution statement

Alberto Pietro Damiano Baltrocchi: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Shafique:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Vincenzo Torretta:** Writing – review & editing, Validation, Supervision, Conceptualization.

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.

Supplementary materials

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