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Net zero carbon buildings: A review on recent advances, knowledge gaps and research directions

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ABSTRACT

As the building sector is a significant contributor to global greenhouse gas emissions and energy consumption, achieving net zero carbon buildings (NZCBs) is vital for reducing environmental impact and meeting global climate goals. This review synthesised recent advances in minimising embodied carbon and operational carbon, identified key research gaps, and proposed future research for achieving NZCBs. It investigates the challenges and opportunities across legislative, financial, cultural, technological, and stakeholder domains. Then, best practices in the decarbonisation of buildings, such as implementation of energy efficiency measures, utilisation of renewable energy sources, and adoption of circular economy principles are examined. Additionally, innovations in new building materials, such as Cross-Laminated Timber (CLT), Cold-Formed Steel (CFS), and Highly Sulfated Calcium Silicate Cement (HSCSC), were found to have substantial potential for reducing embodied carbon. Moreover, technologies like Photovoltaic (PV) panels and modular construction contribute to reducing operational emissions. This study emphasises the importance of comprehensive policies, public education, and collaborative stakeholder engagement in driving the transition to NZCBs. Furthermore, a variety of future research on low-carbon materials, energy efficiency, policies, upfront costs and comparative studies on net zero emissions between developed and developing nations are crucial for scaling sustainable practices globally. The study aims to support global decarbonisation efforts in the built environment by examining best practices, technological innovations, and strategic approaches. These findings highlight the need for continued research and development in sustainable building technologies and the importance of implementing effective policies to achieve a net zero carbon future.

1. Introduction

As the world confronts the escalating challenges of climate change in recent decades, the need to significantly reduce greenhouse gas emissions has become an urgent global priority. The Paris Agreement establishes long-term objectives that direct all countries to significantly decrease global greenhouse gas (GHG) emissions to keep the rise in global temperatures significantly below 2°C above pre-industrial levels and to strive for a maximum increase of 1.5°C, acknowledging that achieving this would greatly diminish the risks and effects of climate change [1]. Complementing this effort, the World Green Building Council (WGBC) called for reducing emissions

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in the building and construction sector by 50 % by 2030 and achieving full decarbonisation by 2050 [2].

This challenge is particularly acute in the construction industry, which significantly contributes to global energy consumption and GHG emissions. Gan et al. [3] emphasised the construction industry's significant role in global energy consumption and GHG emissions. According to the United Nations Environment Programme (UNEP) Report for Buildings and Construction, the building sector is a substantial source of carbon dioxide emissions, accounting for roughly 37 % of total emissions in 2021, as shown in Fig. 1. Residential and non-residential buildings account for 28 % of the total; concrete, steel, and aluminium production contributes around 6 %; bricks and glass account for approximately 3 % of the global emissions [4]. The remaining 63 % of contributions come from the transport sector, other building and construction activities, various other industries, and additional sources [4].

The total operational energy demand of the building sector amounts to 34 %, as in Fig. 2, which includes 30 % of building operational energy demand and 4 % usage by industries that manufacture building materials [4]. Recognising the significance of this, the UK Green Building Council stated that to encourage immediate action and progressively tighten requirements, the framework should be focused on areas where measurement and mitigation are currently feasible: operational energy use and embodied carbon from construction [5]. This highlights the need for a transformative shift toward a net-zero carbon built environment to ensure sustainable practices and minimise environmental impact.

In response to this pressing need, several efforts are made in the building sector to develop various building technologies and environmental assessment methods to encourage energy conservation and support environmental sustainability. Myint and Shafique [5] highlighted that achieving net-zero buildings requires a fundamental transformation in design, construction, and material sourcing practices. Akbarnezhad and Xiao [6] further underscored the variability in a building's carbon lifecycle, influenced by factors such as type, function, location, and climate. Also, the building's carbon lifecycle can differ widely depending on the building's type and function [7], as well as factors such as location, climate, energy sources, building orientation, and massing [8]. Multi-objective optimisation methods, including designing building facades, selecting building shapes, and choosing building components, were conducted to reduce the embodied carbon of the built environment [9]. These methods have also been used to balance embodied and operational energy in buildings and to address parametric design issues in building design [10].

Future advancements in sustainable building practices are shifting toward using local, natural materials with minimal processing and relying highly on specialised knowledge. Numerous research studies have been conducted to identify materials contributing to mitigating carbon dioxide emissions and environmental impacts. Kamel et al. [11] stated that fast-growing biobased materials are extensively used in construction to achieve Low-Carbon Zero-Carbon Buildings (LC-ZCBs) [11]. The selection of bio-based materials for new structures and insulation ensures sufficient biogenic carbon storage to offset embodied carbon emissions [12], and prefabricated light clay-timber elements were found to have a low carbon footprint, excellent thermal insulation, and an outstanding carbon handprint [13]. The construction greenhouse gas emissions are significantly impacted by industries that produce cement, steel bars and frames, and energy sources[14]. High-strength calcium sulfoaluminate cement (HSCSC) can be regarded as an excellent alternative to conventional ordinary Portland cement (OPC) or Portland blast-furnace slag cement (PBSC) [15], and using wood for the structural system is strongly recommended, combined with reducing the floor-to-floor height and span length [16].

Promoting natural resource conservation is crucial to achieving nearly zero-energy buildings and complexes. Effective strategies, such as passive solar designs, efficient energy generators, and renewable energy systems, significantly contribute to achieving net-zero goal in the built environment. On the supply side, fostering innovative architectural and urban design and encouraging the use of passive solar and low-energy designs and energy sources must be considered [17]. Using a combination of 5 % hemp fibre insulation (HF) and 95 % hempcrete (HC) can reduce up to 7.38 % of overall emissions, achieving net zero emissions by 2050 [18]. For a new high-rise building, it is essential to evaluate various green solutions using two primary approaches: passive solar and envelope environment design and renewable energy resources paired with efficient energy generators. Following this evaluation, a detailed optimisation algorithm should be applied to identify the most practical combination of solutions [19].

Since conventional materials appear to postpone reaching net zero emissions by several decades, the only way to accomplish net

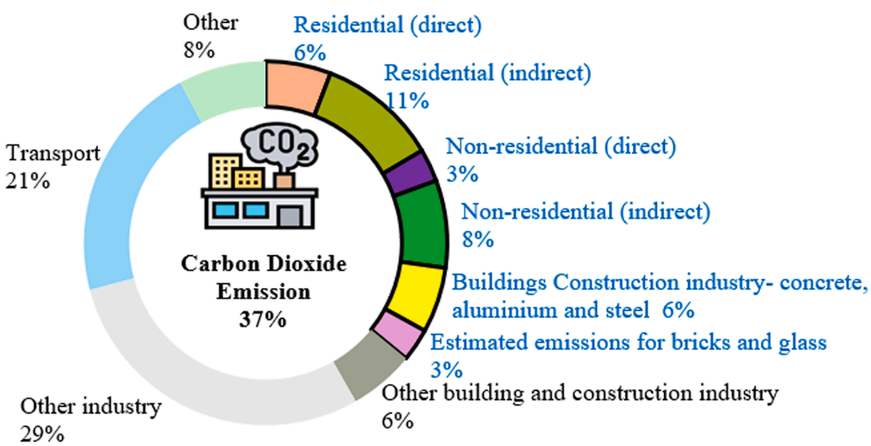

Fig. 1. Carbon emission shares in each sector in 2021[4].

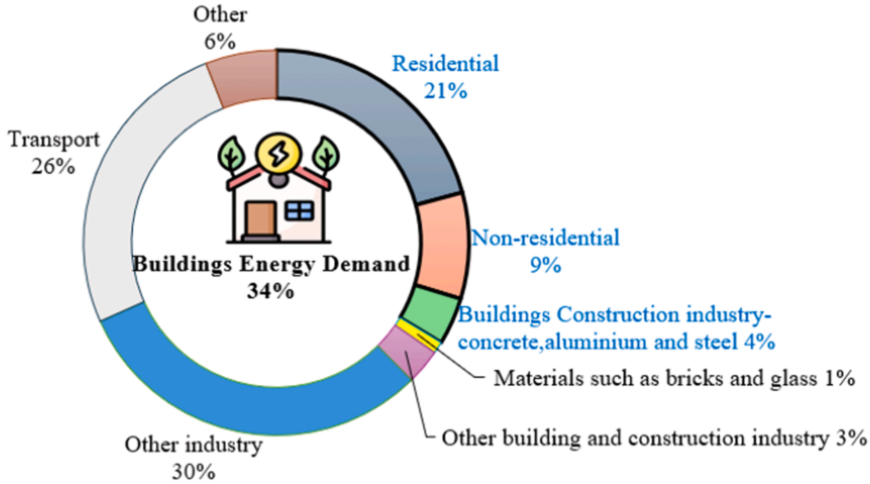

Fig. 2. Energy weight of the building sector in 2021 [4].

zero targets before 2050 is to design new buildings to be carbon-negative in terms of operations and to use photosynthetic materials in their construction [20]. To enhance the design, a range of climate-responsive strategies emphasising passive architecture were employed in the building construction. These strategies feature a high-performance facade, excellent air tightness, and an optimised window design that promotes natural ventilation and maximises daylight [21].

As cities grow and the urgency to mitigate environmental impacts intensifies, the transition to net zero buildings presents significant challenges and knowledge gaps for creating a sustainable future. Addressing these gaps is critical for the success of net-zero carbon initiatives. Understanding the principles, technologies, and policies that support net zero building initiatives is essential for architects, engineers, policymakers, and all stakeholders involved in urban development to close the gaps. Li and Gou [22] recognised the research gap in net-zero building standards for the three largest carbon-emitting nations, China, the United States, and India, and they highlighted that net-zero building approaches, collaborations between the government and multiple organisations, and economic levels are the gaps between developed and developing countries for achieving net-zero buildings. Professionals in the field can develop tailored strategies to bridge the gap in net-zero building between developed and developing nations[22]. Mostafavi, Tahsildoost and Zomorodian [23] identified the research gaps in energy simulation, carbon emission, thermal comfort and renewable energies. To guide the building sector toward achieving net zero by 2050, it is crucial to implement well-designed policies, regulations, and comparable strategies that promote the development of net zero carbon buildings (NZCB). Government policies and building regulations require the construction industry to minimise the environmental impact of their projects [24]. Therefore, stakeholders, especially governments and regulatory authorities, should offer policy support and strengthen initiatives to develop effective laws and regulations for the widespread implementation of NZCB [25].

Although numerous research studies have examined building materials, technologies, and carbon assessment methods and reviewed papers on their findings, there remains a significant gap in reviewing best practices for minimizing carbon, addressing knowledge disparities between countries for global decarbonization, and proposing future directions for achieving net-zero buildings. This study aims to provide a comprehensive review and analysis of the current technologies and methods employed to achieve net-zero carbon buildings. Additionally, it seeks to identify best practices, technological innovations, and strategic approaches that facilitate the transition to net-zero carbon within the building sector. Through an extensive analysis of peer-reviewed literature, this research will pinpoint gaps in existing knowledge, synthesize best practices, and propose areas for future research to support global decarbonization efforts in the built environment.

There are six sections included in this paper. Section 1 introduces the topic and sets the context for the research. Section 2 describes the approach used for the review. Section 3 presents the findings from recent studies. Section 4 highlights the knowledge gaps and Section 5 provides recommendations for future research. Finally, Section 6 discusses the conclusions drawn from the study.

2. Methodology

A systematic literature review effectively allows researchers to evaluate and integrate information on specific topics [26,27]. This review study aims to present recent research on global net zero carbon initiatives, focusing on strategies to reduce embodied and operational carbon emissions in the built environment. It encompasses research and review articles published from 2011 to July 2024 that address net zero carbon reduction in buildings. The first selection criterion was the study's relevance to the topic and its potential to contribute to future research. The second criterion evaluated the study's methodology and effectiveness in deriving results or reaching new conclusions.

This systematic approach ensures that relevant publications meeting the established inclusion criteria are collected and helps minimise bias throughout searching, identifying, evaluating, synthesising, analysing, and summarising findings. The review employs a three-stage method; data acquisition, screening, and synthesis, to assess current technologies and techniques for achieving net zero carbon buildings. The methodology used for this research is depicted in Fig. 3.

2.1. Data acquisition stage

The data acquisition stage is also known as the identification stage. A comprehensive data acquisition process was undertaken across several databases, including Scopus. Scopus was chosen for retrieving articles related to the research topic due to its broad coverage of academic journals across various disciplines, its efficient indexing process, and its availability of recent publications [28, 29]. In the data acquisition phase, studies centred on net zero carbon were chosen for inclusion. The search for relevant data used the terms "*net*," "*zero*," "*carbon*," "*embodied*," and "*building*" combined with the Boolean operator "*AND*." This search was performed in

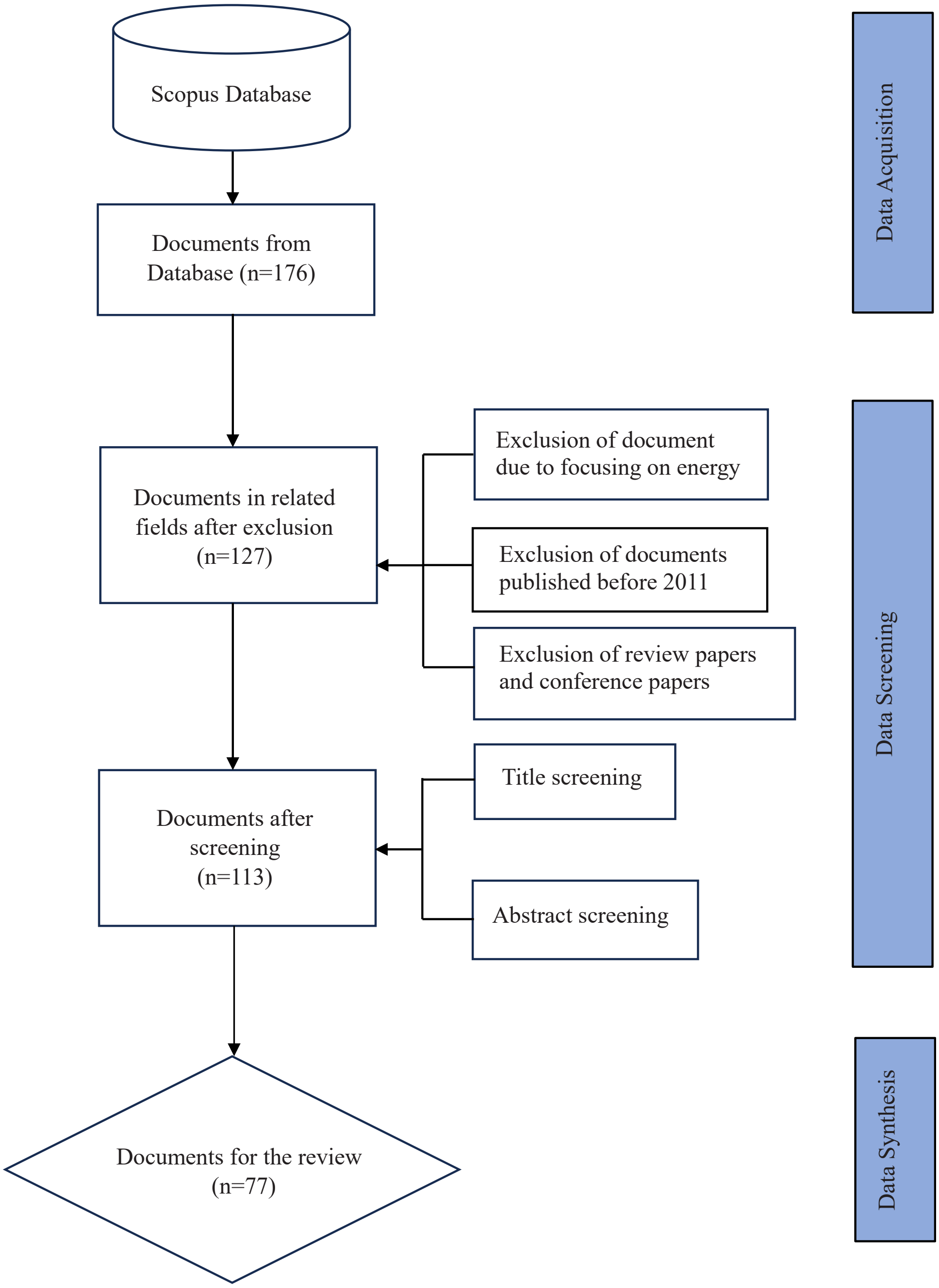

Fig. 3. Methodological flowchart of systematic analysis.

Scopus, renowned for its broad access to high-impact journals and its common use in bibliometric data collection. The search was restricted to "*journal articles*" in "*English*," excluding publications from unrelated subject areas. This approach yielded a total of 176 publications.

2.2. Data screening stage

In the screening phase, 176 articles were initially reviewed by their titles and abstracts. Articles focused on areas outside the subject of energy and those published before 2011 were excluded, resulting in 171 publications being retained. Subsequently, review and conference papers were excluded, limiting the search to journal articles and leaving 127 documents. Eight were immediately discarded after excluding papers of titles and abstracts unrelated to net zero carbon buildings, and eight were immediately discarded. Of the remaining articles, 110 were accessed in full text, with three inaccessible documents. From this screening phase, 113 papers were chosen for detailed data extraction. These papers were classified based on content and carefully reviewed to analyse publication trends.

2.3. Data synthesis stage

At this stage, the categorisation analysis also includes extracting relevant information that pertains to the research aims and objectives. In this final stage, 77 articles were categorised based on the content and thoroughly reviewed to identify publication trends over 13 years. This categorisation process also involved extracting the research relevant to the net zero carbon strategy, such as reducing embodied and operational carbon in the built environment. Moreover, other aticles and reports which discuss the importance of this research topic were also included in this review study.

3. Research analysis

3.1. Research trend on net zero carbon

Analysing the annual publication trends of articles allows researchers to measure the degree of interest and focus that a specific subject area has received [30]. Scopus offers broader coverage of scientific publications than other databases [31], and it has the likelihood of accessing more up-to-date publications [29]. According to Scopus, 18 articles related to net zero carbon were published from 2011 to 2019, indicating an increasing focus on mitigating carbon emissions. The peak in publications occurred between 2020 and July 2024, with 81 publications likely driven by the goal of achieving carbon reduction targets. During this period, the World Green Building Council, following the Paris Agreement, established a target for new buildings to achieve net zero carbon in operation by 2035 and for the entire built environment to achieve net zero operational carbon by 2050 [32]. The notable increase in publications from 2020 to July 2024 reflects the global emphasis on net zero carbon strategies.

Fig. 4 illustrates annual publication trends from 2011 to July 2024, based on Scopus data. Despite this growing body of work, few studies focus on net zero carbon buildings. To fill this research gap, this study aims to review the technologies and methods used to decarbonise the built environment.

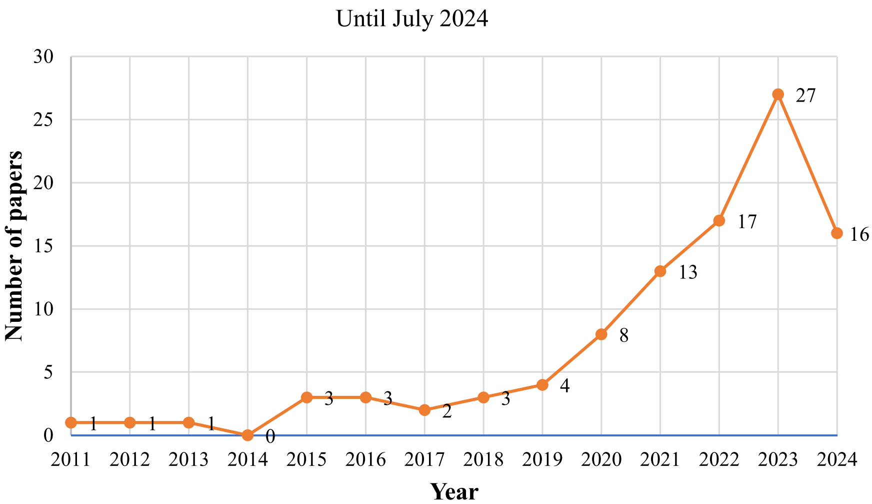

Fig. 4. Publication of documents on net zero carbon by year according to Scopus.

3.2. Global research on net zero carbon buildings

Several countries and regions worldwide have backed these initiatives by endorsing net zero carbon buildings as a central government strategy to tackle climate change [33,34]. These countries have incorporated net zero carbon buildings into their building energy codes and policies and detailed the scope of energy use and calculation methods [35].

World Business Council for Sustainable Development (WBCSD) stated embodied carbon as the carbon contained in the materials required for building, renovating, and demolishing structures, as well as the energy consumed during these processes, and also operational carbon as the carbon arising from the energy consumed in the regular functioning and maintenance of the building [36]. The European Commission has recently set an ambitious target for all new buildings to achieve zero emissions by 2030, a key component of its broader strategy to decarbonise the EU's building stock by 2050 [37]. The US Department of Energy has set targets to reach zero-energy homes by 2020 and zero-energy commercial buildings by 2025 [38]. The UK Green Building Council initiated a whole-life carbon roadmap to achieve net zero carbon across all stages of a building's lifecycle, including construction, operation, and demolition [2]. Reaching net zero embodied carbon in buildings across Japan by 2050 is achievable with current technologies, such as decarbonised electricity, low-carbon steel, low-carbon concrete, increased use of timber, optimised design, and extended building lifespan [39]. Therefore, all government and local administrations have adopted net zero carbon policies and initiatives to transition all buildings to zero carbon [40].

Kamel et al. [11], Greene et al. [41] and Salama et al. [42] researched residential and office buildings in the United States of America using biobased materials, PV panels, and structural frames varying in configurations, loading conditions, span lengths, and column heights to study their effectiveness in achieving net zero carbon and energy buildings. Jankovic, Bharadwaj and Carta [20], Sharples and Newberry [43], and Harper and Norman [44] studied residential buildings in the United Kingdom to achieve net zero targets by reducing embodied and operational carbon. Hospitals, residential buildings and parks in China are investigated to relieve the embodied carbon by adjusting the window-to-wall ratio, the design management, and to obtain net zero energy by using the roof and facade PV [9,45] and [46]. The high-rise buildings in Hong Kong are analysed to perform net zero buildings by changing orientation, Design for Manufacturing and Assembly (DfMA) and using renewable energy generated by photovoltaics (PV) and bio-diesel combined cooling heating [21] and [47].

The International Energy Agency (IEA) report underscores that energy efficiency and electrification, along with the availability of market technologies, are the leading factors advancing the building sector toward achieving net zero emissions [48]. Satola et al. [49]

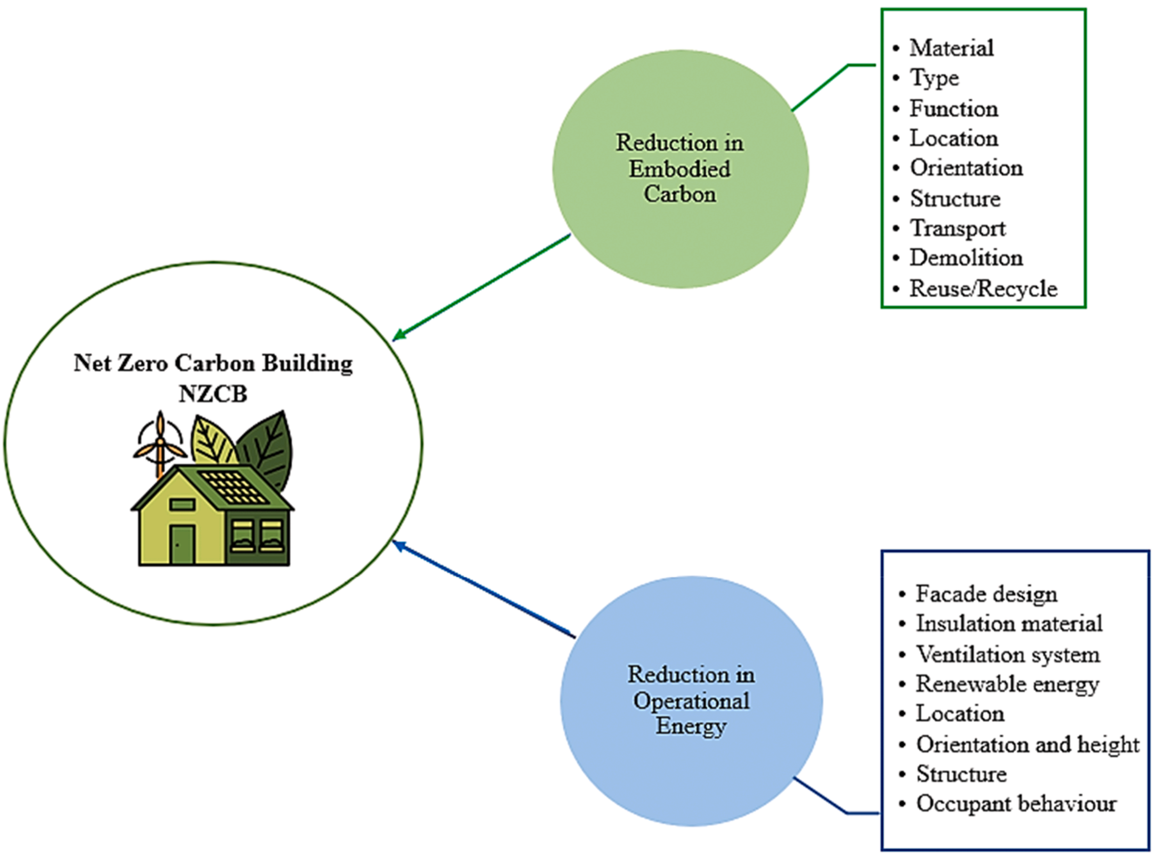

Fig. 5. Key influencing factors for implementing net zero carbon building, as extracted from previous studies.

stated that these available market technologies, such as efficient building envelopes for new and existing buildings, energy-efficient appliances, heat pumps, and designs that emphasise bioclimatic and material efficiency, fuel the shift to net zero [49]. Therefore, the literature reveals that researchers from different countries have concentrated on embodied carbon emissions to achieve net zero targets in the construction industry. Based on the previous studies, the key factors used for research on NZCB are listed in (Fig. 5).

Global research in the building sector has focused on achieving Net Zero Carbon Building (NZCB), which can be achieved by reducing embodied and operational carbon. Embodied carbon can be reduced by minimising emissions from the building's materials, type, function, location, orientation, structure, transport, demolition, and reuse/recycling processes. Reduction in operational carbon focuses on decreasing emissions through efficient facade design, insulation materials, ventilation systems, renewable energy usage, location, building orientation and height, structure, and occupant behaviour. Net zero buildings aim to balance the carbon and energy they consume with the carbon and energy they produce, resulting in a net zero footprint over their lifecycle. Understanding the key influencing factors is crucial for successfully implementing and operating net zero energy buildings. Addressing these key influencing factors holistically can significantly enhance the performance and sustainability of net zero buildings throughout their lifecycle, ensuring they meet their goals effectively.

3.3. Recent advances in net zero carbon buildings studies

Understanding and addressing the key influencing factors lays the foundation for advancing research and implementation strategies in Net Zero Carbon Buildings (NZCB). This section examined recent advances in NZCB studies, focusing on innovative measures, building types, and carbon assessment methods that are driving progress in the field. Net Zero Carbon Building (NZCB) is a building that achieves zero carbon status when the greenhouse gas emissions linked to its operational and embodied footprint throughout its entire lifecycle, including disposal, are zero or negative [50]. Many countries and regions worldwide have backed these initiatives by championing NZCBs as a central government strategy for combating climate change [33,51]. Consequently, the concept of a NZCB has appeared as an innovative approach to achieving zero emissions in the building sector.

This paper reviewed the selected papers from the Scopus database as presented in Table 1, and the findings were discussed in the following three sub-sections based on analysing the critical research areas: (1) Key technological findings, (2) Advances in types of buildings, and (3) Carbon assessment methods.

3.3.1. Key technological findings

Integrating advanced technologies across the supply chain has a significant potential to reduce greenhouse gas emissions. This study highlights innovations that support decarbonisation, including the development of new building materials, energy-efficient technologies, and advancements in achieving net zero buildings.

Yamashita and Serrenho [39], Kamel et al. [11], Greene et al. [41], Torabi and Evins [16] and Päätalo et al. [13] found that timber buildings can significantly reduce embodied carbon emissions. Watari, Yamashita, and Serrenho [39] examined timber buildings in Japan and discovered that increasing the use of timber structures could save up to 35 % of annual emissions by 2050. Similarly, Jankovic, Bharadwaj, and Carta [20], Zhou, Tam, and Le [9], Watari, Yamashita, and Serrenho [39], and Myint and Shafique [5] studied how designing buildings to be carbon-negative could be highly effective for net zero emissions. Also, Zhou, Tam, and Le [9] conducted a study in China on an eight-story residential building using Building Information modelling-based LCA. Their findings highlighted the potential of the early design stage to save 32.5 % of emissions.

Greene et al. [41] and Gigante and De Masi [53] explored the use of Cross-Laminated Timber (CLT) in construction and concluded that it is an effective material for reducing carbon emissions. Ahmed et al. [52] further noted that CLT meets acceptable standards under combined lateral and gravity loads. Comparative studies between reinforced concrete buildings and those constructed with CLT reveal that CLT structures can store considerable amounts of carbon, positioning them as a promising alternative for future net zero carbon cities. Iuorio, Gigante and De Masi [53] studied cold-formed steel (CFS) systems and cross-laminated timber (CLT) materials in Italy. The study emphasised that CFS technology with those of cross-laminated timber is an innovative off-site technology for the development of nearly zero energy buildings. Kim et al. [15] examined the feasibility of using Highly Sulfated Calcium Silicate Cement (HSCSC) as an alternative to traditional cement, highlighting its low embodied energy and reduced environmental impact. The study compared HSCSC with ordinary Portland blast furnace slag cement (PBSC) and Portland cement (OPC), finding that HSCSC's carbon footprint is only 5.8 % of OPC's and 13.3 % of PBSC's. Design for Manufacturing and Assembly (DfMA), such as Modular Integrated Construction (MiC) or prefabricated parts, can reduce embodied carbon [13,47].

Rising energy demand and carbon emissions may have driven the growing research interest in residential Net Zero Energy Buildings (NZEBs) [49]. Concerns about energy consumption shifted towards the building sector, encompassing residential, commercial, and public structures [66]. Reducing operational carbon has also been a major focus of research. Jankovic, Bharadwaj and Carta [20] found that PV panels should be used for minimising operational energy, and Luo *et al.* [46] studied that PV on the roof and facade can boost the energy-saving rate by up to 170 %. Additionally, the building design such as the window-to-wall ratio [9], a high-performance facade, effective airtightness, and optimised window design [21], had proven effective in reducing energy demand. Hachem-Vermette [67] discovered that incorporating PV panels into facades with geometric patterns significantly enhances potential electricity generation by maximising the surface area exposed to solar radiation. Luo *et al.* [46] conducted 3 case studies, including monocrystalline silicon solar cells for roofs and emerging PV materials, such as perovskite solar cells for facades. The findings revealed that while their combined use results in the highest carbon emissions during the construction phase, it achieves the lowest emissions during the operational phase. Newberry, Harper and Norman [44] highlighted that the proportion of renewables in the grid's energy mix significantly affects operational carbon levels. Their study also demonstrated that combining Integrated Environmental Solutions

Table 1
Net zero carbon buildings studies identified in the literature.

Ref.	Location	Occupancy Type	Method	Building Structure	Findings
[20]	United Kingdom	Residential building	Dynamic simulation modelling for energy performance	Concrete blockwork and Brick masonry	• Conventional materials hinder the attainment of net zero emissions. • Achieving net zero targets: designing new buildings to be carbon-negative in their operations and utilising photosynthetic materials in construction.
[52]	Saudi Arabia	Ten-story residential building	Lifecycle Carbon Assessment (LCA)	Reinforced concrete	• Cross-laminated timber (CLT) building met acceptable standards under combined lateral and gravity loads. • Using CLT or hybrid buildings can reduce carbon emissions
[39]	Japan	Residential and non-residential buildings	Material Flow Analysis (MFA) model and LCA	Steel frame, Concrete block, Reinforced concrete, Timber and Others	• Using timber structures, potential annual emissions can save up to approximately 35 % by 2050. • Design optimisation and enhanced building lifespan provide an additional 10 % savings
[47]	Hong Kong	21-storey residential tower	Building Information Modelling based LCA	Reinforced concrete	• Orientation can optimise lifecycle performance • Low-carbon materials account for 30.90 % of the lifecycle carbon emissions of residential buildings. • Design for Manufacturing and Assembly (DfMA), such as Modular Integrated Construction (MiC) or prefabricated parts can reduce embodied carbon.
[9]	China	8-Story residential building	Building Information Modelling based LCA	Reinforced concrete	• The early design stage has the potential to save 32.5 % of emissions • The window-to-wall ratio and the number of floors significantly affect embodied and operational impacts.
[53]	Italy	School	LCA	Reinforced concrete	• Cold-form steel (CFS) walls have the highest impact • Cross-laminated timber (CLT) walls are the least sustainable. • Environmental impacts of 1 m^2 of walls and floors of CFS technology with those of cross laminated timber is an innovative off-site technology for the development of nearly zero energy buildings.
[11]	United States of America	2 story residential building	Dynamic LCA	Timber frame	• Biobased materials can be applied to reduce embodied carbon in buildings. • PV panels should be used to reduce operational carbon.
[54]	Australia	Residential and commercial buildings	Macro-economic simulation model	Australia's built environment	• Adopting renewable energy investment significantly reduces total emissions. • Electrification of buildings and the adoption of electric vehicles results in a 94 % reduction in total emissions.
[55]	Canada	Residential buildings	Athena Impact Estimator	Concrete and wood structure	• The negative impact of carbon emission from material production can be overcome by adding exterior wall insulation.
[12]	Italy	Office building	LC	Reinforced Concrete	• A reduction of 91 % in embodied carbon compared to standard new construction can be achieved, with bio-based materials compensating for the remaining carbon.
[41]	United States of America	Office building	LCA	Cross-laminated timber and glulam, Steel framing and a mass timber	• The mass timber design provides a reduction in embodied carbon of 80–99 %.
[56]	Sweden	Multi-family residential buildings	Abatement technologies	Reinforced Concrete	• Greenhouse gas emissions can be cut by up to 40 % using existing technologies and practices. • Potential reductions in emissions could reach 80 % by 2030 and 93 % by 2045.
[57]	Madagascar	Residential buildings	Design-Builder software		• Coastal tropical regions are highly conducive to designing Net Zero Energy Developments.

(continued on next page)

Table 1 (*continued*)

Ref.	Location	Occupancy Type	Method	Building Structure	Findings
[58]	Portugal	Residential buildings	BIM-based LCA	Reinforced concrete, Masonry	• Masonry Building 1 results in an 11 % reduction in CO_2 emissions and a 12 % decrease in energy consumption. • Masonry Model 2 shows a 39 % reduction in CO_2 emissions and a 41 % reduction in embodied energy.
[45]	China	Hospital, residential, park	LCA	Light steel, shear wall, frame, frame shear wall	• The integrated management strategies can help reduce carbon emissions from abandoned landfills by 11.9–34.8 times.
[16]	Canada	Residential building	LCA	Steel, wood	• Combining wood structures with floor height and span length considerations can minimise the carbon footprint.
[13]	Finland			Light clay-timber wall element	• Prefabricated light clay-timber elements support low carbon emission and thermal insulation.
[59]	Serbia	Residential building		Photovoltaics (PV) system	• A Positive-Net Energy Building (PNEB) is achieved with a thermal insulation thickness of 0.15 meters. • Using a thickness of less than 0.15 m, it will be a Negative-Net Energy Building (NNEB).
[60]	South Africa	Residential building	LCA	Sandbag building technology (SBT)	• Carbon dioxide equivalent (CO_2e) emissions depend heavily on the availability of local sand and whether the process is manual, automated, or both. • The sandbag method is complicated for multi-storey buildings due to the weight.
[61]	New Zealand	Residential building	LCA	Steel Roof	• The pre-painted steel coils manufactured globally had less than 70 % of the emissions compared to locally manufactured ones.
[42]	United States of America	Single-story buildings	LCA	steel portal frames	• The embodied carbon per unit volume of a steel frame depends on its configuration, loading, span lengths, and column heights. • Increasing member divisions, design variables, and non-prismatic segments can notably lower the average embodied carbon.
[62]	Australia	Residential buildings	LCA	Timber, Steel	• It is necessary to reduce raw materials by adopting circular economy approaches, which circulate building materials throughout the supply chain and minimise raw material extraction.
[21]	Hong Kong	Mixed-use building		Photovoltaics (PV) and bio-diesel combined cooling heating and power (CCHP) system	• A high-performance facade, effective airtightness, and optimised window design can decrease energy demand by 20 %. • Energy-efficient air-conditioning (A/C) systems also provide ultra-low energy usage.
[63]	Egypt	Scientific centre	Dynamic LCA	Waste-derived materials and recycled steel reinforcement	• CO_2 emissions mainly come from reinforced concrete, while finishes, internal walls, and windows are minor sources of emissions.
[64]	Norway	Residential buildings		Lightweight timber-framed construction with timber facades	• For the zero energy building cases, embodied emissions accounted for minor sources for approximately 60–75 % of the total embodied and delivered energy emissions in the baseline results.
[43]	United Kingdom	Residential complex with integrated commercial and recreational areas	LCA	Preassembled façade, modular bathroom units, utility risers and partition systems, machinery and equipment, and electrical wiring bundles	• The life-cycle emissions of the prefabricated building outperform the business-as-usual model despite being a low band in the Low Energy Transformation Initiative (LETI) labelling system • Prefabrication in new builds or refurbishment projects is crucial for

(*continued on next page*)

Table 1 (*continued*)

Ref.	Location	Occupancy Type	Method	Building Structure	Findings
					reducing building carbon emissions by at least 10 %.
[15]	South Korea		LCA	Highly sulphated calcium silicate cement (HSCSC)	• HSCSC is a superior eco-friendly option compared to conventional Ordinary Portland Cement (OPC) or Portland Blast Furnace Slag Cement (PBSC). • HSCSC poses minimal risk to human health.
[65]	Australia	Commercial building	LCA	window-to-wall ratio (WWR) of 31 %	• Reuse provides more significant net benefits to global warming potential (GWP), total use of renewable primary energy resources (PERT), and total use of non-renewable primary energy resources PENRT than recycling. • Extending the façade lifespan decreases the variability in impact indicators across various end-of-life (EoL) scenarios. • Choosing a façade with better operational savings improves life cycle benefits
[46]	China	Multi-objective optimisation (MOO) model of park buildings	multi-objective optimisation (MOO) model	No PV, only roof PV, and both roof and facade PV,	• Without PV, energy savings of 22.35 % can be achieved compared to the benchmark building. • Roofing with PV significantly enhances the program's payback benefits. • PV on the roof and facade can boost the energy-saving rate by up to 170 %. • Roof and façade PV result in the highest carbon emissions during the construction phase but the lowest during the operational phase.
[5]	Myanmar	Residential Building		Reinforced Concrete	• Evaluate embodied carbon during the preliminary design stage. • In scenarios involving low-carbon materials, timber highlights its effectiveness in carbon sequestration. • Emphasize the use of locally accessible low-carbon materials for construction.
[44]	United Kingdom	Residential Buildings		Different insulation materials	• The percentage of renewables in the grid's energy mix has a significant impact on operational carbon levels. • Combining Integrated Environmental Solution Virtual Environment (IESVE) and One Click LCA simplifies life cycle assessment by modelling energy use for operational carbon and automating material data transfer for embodied carbon evaluation.

Virtual Environment (IESVE) with One Click LCA streamlines lifecycle assessment by modelling energy use for operational carbon and automating material data transfer for embodied carbon evaluation [44].

In achieving decarbonisation in construction, systematic management strategies can decrease the carbon footprint of structural buildings [45]. Also, early design interventions can lead to substantial emission reductions, as demonstrated by the 32.5 % potential reduction for mid-rise buildings in China [9].

3.3.2. Advances in types of buildings

Based on the number of reviewed papers in this study as in Table 1, the majority of the researched buildings are residential, and the researchers studied how to minimise the embodied carbon of the buildings according to their types.

Depending on the building materials used in construction, it is evident that decarbonisation can be significantly achieved in timber buildings and in hybrid structures incorporating timber. Studies by Ahmed *et al.*[52], Besana and Tirelli [12], Heidari *et al.* [55], Illankoon, Vithanage and Pilanawithana [62], Kristjansdottir *et al.* [64], Kamel et al. [11], Torabi and Evins [16], Päätalo et al. [13] and Myint and Shafique [5] conducted research on the timber structure and found that timber is an effective material for decarbonisation. Greene et al. [41] found that the mass timber buildings can reduce the carbon emission to 80–99 % and Watari, Yamashita and Serrenho [39] investigated that by using timber buildings, the annual carbon emission can reduce to 35 % by 2050. In the research on steel buildings, Iuorio, Gigante and De Masi [53] investigated that Cold-form steel (CFS) has the highest carbon impact among wood and galvanised metal. Sazedj, José Morais and Jalali [58] studied two types of masonry buildings and concluded that 11 % and 39 % reduction in embodied carbon.

For operational carbon emissions, it was highlighted that building usage significantly impacts the amount of carbon that can be reduced. Nejat et al. [68] discovered that residential buildings use comparatively more energy than commercial buildings and contribute a significant portion of carbon emissions within the building stock. Among the studies in this review, Costa et al. [69] and Ohene, Chan and Darko [70] proposed that research on achieving the net zero goal in office buildings is still in its early stages, highlighting the need for further studies. Moreover, designing for net zero is crucial not only for new constructions but also for retrofits and renovations [71]. Many studies have been carried out for different building types and found that mass timber buildings and combined timber buildings can significantly reduce the carbon footprint.

3.3.3. Carbon assessment methods

Building embodied carbon assessments are comparable to the more widely adopted and standardised Life Cycle Assessment (LCA) methodology, which quantifies carbon emissions throughout a building's life cycle [72]. Life Cycle Assessment (LCA) is a standardised approach for evaluating a system from production to end-of-life, including raw material extraction, manufacturing, transportation, use, reuse, maintenance, recycling, and final disposal. This methodology is organised into a four-step framework as outlined in ISO 14040:2006 [73]. There are three main methods for compiling a Life Cycle Inventory (LCI): process-based analysis, input-output analysis, and hybrid-based analysis [74]. Process-based analysis is a bottom-up method that breaks down the system into a series of processes throughout its life cycle. Input-output analysis is a top-down approach that uses macroeconomic data from the relevant economic sector. Hybrid analysis combines both methods, employing process data and addressing any gaps with input-output data to mitigate the limitations of each approach [75]. Several databases offer information on embodied carbon and energy, focusing mainly on the material extraction and manufacturing stages, often called the 'cradle to factory gate' phase. Additionally, various software tools have been developed to assess the embodied energy and carbon of individual buildings [76].

Most studies reviewed in this paper used Life Cycle Assessment (LCA) to estimate the carbon footprint. Building Information Modelling (BIM) software is widely employed in the construction sector, so BIM-based LCA methods are also being utilised as an advanced technique in achieving net zero carbon buildings. Chen et al. [77] discovered that a BIM-based LCA system provides an efficient and automated method for evaluating different design options, supporting the development of low-carbon buildings. Also, Arenas and Shafique [78] stated that integrating technologies like BIM and LCA can significantly speed up design and construction processes.

3.4. Identification and categorisation of decarbonisation in embodied carbon emissions

Buildings generate carbon emissions at every stage of their lifecycle, encompassing construction, utilisation, demolition, and disposal. Numerous studies have been conducted on building materials, including low-carbon materials, to contribute to reducing embodied carbon in buildings. According to the research results in this review, the key elements which can significantly minimise embodied carbon emissions are listed in Table 2.

The data provided in Table 2 identifies essential materials and strategies for decarbonising buildings, drawing on various studies to support these recommendations. Various studies for net zero buildings focusing on primary construction materials such as timber, concrete, and steel were conducted, and timber is the most significant material in minimising embodied carbon. Greene et al.[41] discovered that the mass timber design can reduce embodied carbon by 80–99 %. Additionally, design practices such as prefabrication [15] and [43], as well as design for manufacturing and assembly [47], are effective technologies in decarbonisation for the building construction sector.

Gan *et al.* [47] and Myint and Shafique [5] studied low-carbon materials, and Kamel et al. [11] and Besana and Tirelli [12] proved biobased materials as the decarbonisation materials. Applying bio-based materials in building frameworks is a practical method for

Table 2
Key elements in embodied carbon emissions reduction strategies for the selected case studies.

Key elements used for decarbonisation		Ref.
Building Geometry	Building material	
-	Timber	[5,16,39,64]
-	Cross Laminated Timber (CLT)	[9,20,41,45,52,53,79]
-	Steel	[11,16,39,41,42,45,52,54,61,62]
-	Concrete	[20,52,39,47,9,53–55,12,56,58,5]
-	Cement	[15,39]
-	Cold-Formed Steel (CFS)	[9,53]
-	Biogenic insulation materials	[12,18,53,57]
-	Aluminium, copper, timber and glass	[11]
Wall, floor, roof, windows, airtightness	-	[20,47,54]
Floor slabs	-	[9,16]
Structures with frame, frame shear wall, shear wall	-	[45]
Reuse and retrofit strategies integrating PV panels into the façade with geometric patterns.	-	[12,41,62,65]

sequestering carbon, lowering building emissions and converting them into carbon storage systems. These materials capture carbon dioxide during their development, with a portion of the carbon stored in the plants once harvested [80]. By applying measures throughout the supply chain, Karlsson *et al.* (2021) conducted an assessment demonstrating the potential to reduce greenhouse gas emissions associated with constructing the building systems for multi-family housing by up to 40 %, using the best available existing technologies [56]. Compared with conventional demolition and landfill waste methods, systematic management strategies can decrease the carbon footprint of structural buildings by 150.7–246.8 $kgCO_2$-e/m^2. This amounts to a carbon savings of 11.9–34.8 times higher than the emissions resulting from landfill disposal [45].

Different strategies have been assessed since materials with reduced embodied carbon help minimise a building's carbon footprint [81]. These include practices such as recycling, repurposing, and reducing waste generated from construction and demolition [82], improving material efficiency [83], improving resilience, and using bio-based materials with reduced embodied carbon emissions [84]. Carbon emissions occur at all stages of the lifecycle of the building, from construction to disposal, necessitating comprehensive approaches to reducing embodied carbon. Moreover, most studies investigated that using low-carbon materials [5,13,47], biobased materials [11,12,18,53,57], recycling materials [65,82] and reusing materials [82]can highly impact on decarbonisation in building constructions.

By integrating these key elements and strategies, the studies collectively demonstrate how various materials and design practices can contribute to decarbonising the built environment, aiming for a significant reduction in embodied and operational carbon emissions. Overall, the findings underscore the critical need for innovative materials and strategies in building design and construction methodology to significantly reduce carbon emissions, contributing to global decarbonisation efforts in the built environment.

3.5. Identification and categorisation of decarbonisation in operational carbon emissions

The relevant studies of net zero emission buildings organised by Scopus extract the technological advances in operational carbon. Table 3 summarises critical design and operational carbon emissions reduction strategies used in selected net zero case studies.

According to Hachem-Vermette [67], potential electricity generation is boosted substantially by integrating PV panels into the façade with geometric patterns and increasing the available surface area exposed to solar radiation. Rafiei and Adeli [19] studied the fact that in a new high-rise building, various green solutions should be assessed, concentrating on two main areas: passive solar and building envelope design and integrating renewable energy sources with efficient energy generators to achieve net zero energy.

For energy efficiency, studies such as Newberry, Harper and Norman [44], Päätalo *et al.* [13], Heidari *et al.* [55], Karlsson et al. [56] highlight that improved insulation materials in building envelopes significantly reduce heating and cooling energy demands, thereby enhancing energy efficiency and lowering operational carbon emissions. Specifically, Päätalo *et al.* [13] proposed the use of prefabricated light clay timber as an effective insulation material, while Gan *et al.* [47] identified external façades and opaque glass/glazed elements as energy-efficient solutions. Additionally, Ng *et al.* [21] emphasized that energy-efficient air-conditioning (A/C) systems play a crucial role in achieving ultra-low energy consumption in buildings.

Passive solar design is a particularly effective method for minimising energy use, focusing on optimal building factors, such as location, climate, orientation, and building massing to ensure adequate heat and ventilation. Energy-efficient combinations of variables, such as window and wall features, can significantly reduce annual thermal energy consumption, resulting in a 32 % reduction in annual thermal energy consumption [23]. The proportions of embodied and operational carbon contributing to buildings' total life cycle carbon emissions can vary significantly based on the building type and function [7] and factors such as location, weather system, energy type used, site orientation, and building massing [8]. Additionally, the window-to-wall ratio and the number of floors play critical roles in optimizing energy efficiency and balancing environmental impacts. Gan et al. [47] and Zhou, Tam and Le [9] highlighted that building geometry, specifically orientation, window-to-wall ratio, and the number of storeys, has a substantial impact on reducing operational carbon emissions.

Additionally, Jankovic, Bharadwaj and Carta [20], Rafiei and Adeli [19], and Mostafavi, Tahsildoost and Zomorodian [23]

Table 3
Key elements used in operational carbon emissions reduction strategies and findings for the selected net zero case studies.

Key element	Ref.	Main findings
Photovoltaic (PV) modules	[11,20,21, 46,59]	Utilising photosynthetic materials in new construction enhances the reduction of operational carbon.
Solar thermal panels	[19,20,23]	Passive solar design is needed to evaluate to achieve net zero energy.
External façade, opaque glasses/ glazed elements	[47]	PV on the roof and facade can boost the energy-saving rate by up to 170 %.
Renewable energy	[19,21,23, 54]	On-site renewable energy offsets the total life-cycle carbon emissions produced by PV and bio-diesel combined cooling, heating, and power (CCHP) systems.
Prefabricated light clay-timber	[13]	Using prefabricated light clay timber proves a low carbon footprint and effective thermal insulation.
Insulation material	[13,44,56]	Enhanced thermal insulation in building envelopes significantly reduces heating and cooling energy demands, thus lowering operational carbon emissions.
Exterior wall insulation	[55]	The benefits of adding exterior wall insulation generally outweigh the drawbacks associated with its carbon emission.
Air-conditioning systems	[21]	Energy-efficient air-conditioning (A/C) systems also contribute to achieving ultra-low energy use.
Weather Condition	[9,57]	Operation carbon is reduced due to the climate conditions and environmental geo-location.

investigated that passive solar designs highly impact decreasing energy usage in buildings. A study on buildings in Hong Kong found that a 20 % reduction in energy demand can be achieved through improvements in facade design, effective airtightness, and optimised window design [21]. It was concluded that U-shaped and octagonal layouts of residential high-rise buildings (HRBs) obtain a higher electricity generation than the combined energy consumption for cooling and heating, regardless of the facade type [67]. Therefore, these factors should be carefully considered and integrated into the design process for future newly constructed buildings.

Renewable energy sources such as solar, wind, geothermal, and biomass energy are employed to replace fossil fuels and support sustainability. Incorporating renewable energies into buildings, particularly residential types, can decrease reliance on fossil fuels. The integration of Photovoltaic (PV) modules in buildings enhances the reduction of operational carbon emissions [11,20,21,46,59]. Also Gan et al. [47] found that PV systems can save energy usage by up to 170 %.

Therefore, integrating renewable energy solutions, such as photovoltaic (PV) panels, into building designs can significantly enhance energy efficiency and reduce operational carbon emissions, particularly when combined with energy-efficient building materials and passive solar design strategies. The use of advanced insulation materials, optimised building geometry, and energy-efficient systems like air conditioning and façade design play critical roles in minimising energy consumption and improving overall sustainability. Incorporating these design principles and renewable energy sources will be crucial in achieving net zero energy buildings and contributing to decarbonisation efforts in the built environment.

4. Research gaps and challenges in net zero buildings

Despite significant studies aimed at understanding and implementing strategies to reduce embodied and operational carbon emissions, research gaps and challenges in achieving Net Zero Carbon Buildings (NZCBs) persist. The NZCB target remains challenging to attain in practice, as evidenced by the scarcity of published case studies in the literature, despite existing technologies that can meet the goal [12]. This reflects the need for further exploration of barriers to adaptation and implementation, including significant hurdles that must be addressed [25].

As the challenges, Osmani and O'Reilly [85] identified legislative, financial, cultural, and design, while Godin et al.[86] examined the market, state involvement, and cultural and technical obstacles to attaining net zero energy homes.The policies and regulations play a key role in stimulating market demand for Net Zero Carbon Buildings (NZCBs) by guiding and motivating stakeholders to adopt low-carbon practices [87]. Although net zero standards for buildings have been considered, they have not been widely implemented, likely due to the complexities related to metrics, compliance, and accountability [88]. To effectively reduce energy consumption and greenhouse gas (GHG) emissions, policies must address both resource conservation and climate mitigation holistically, as energy-focused policies alone are insufficient to meet climate targets [89]. In parallel, governments and housing finance institutions should develop creative financing strategies and share cost information through websites, newsletters, and social media platforms [25].

Based on the findings from the previous studies, this paper organised the distinct research gaps and challenges in NZCBs into areas where knowledge is insufficient or further exploration is required, as shown in Fig. 6.

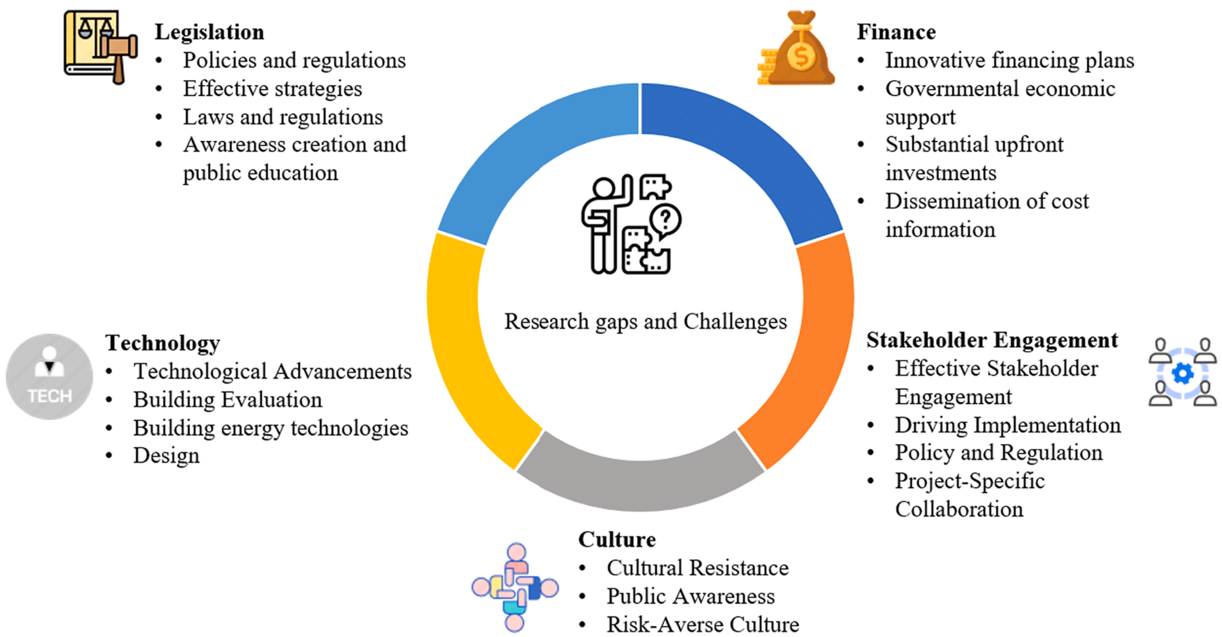

Fig. 6. Research gaps and challenges in net zero buildings.

4.1. Legislation

Practical strategies for integrating renewable energy sources into the building design and operation phases to achieve net zero carbon status have not yet been fully developed. There is a gap in net zero standards between developed and developing countries. Complexities in compliance, accountability, and metrics have hindered the widespread implementation of net zero building standards, especially in developing countries, where legal frameworks for NZCBs are often lacking. Research on effective policy frameworks and incentive mechanisms that can drive the adoption of net zero carbon buildings is still developing. Many developing countries lack the necessary policies, laws, and regulations to mandate net zero building practices, making the enforcement of comprehensive greenhouse gas (GHG) reduction strategies a significant hurdle. This gap underscores the need for robust legislative action to achieve climate goals.

Raising awareness and garnering public support through policy initiatives is crucial for overcoming legislative and sociocultural barriers. However, efforts to educate the public on decarbonisation at a national level remain inadequate. Addressing this gap through public education campaigns and policy-driven awareness programmes can play a pivotal role in accelerating NZCB adoption and achieving broader climate objectives.

4.2. Finance

Obtaining funding and accessing information are major challenges in advancing and implementing NZCBs. The critical gap in the building industry's finance is designing new financial models and plans that enable investments in emerging technologies and sustainable projects. The lack of specific government economic support presents a substantial obstacle. Insufficient government funding and financial incentives create barriers, particularly for developers who must bear most of the financial burden. High upfront costs are a big challenge since NZCBs require significant initial investments, which deter private customers who are uncertain about recouping these costs.

4.3. Culture

Cultural resistance to adopting NZCBs is rooted in the construction industry's substantial investment and the prevailing risk-averse attitudes. Heffernan *et al.* [90] and Jones [91] stated that a significant barrier is the lack of public awareness about low-carbon living and Zero Carbon Buildings.Overcoming reluctance or opposition to new technologies, practices, or ideas, which may be rooted in tradition, fear of change, or unfamiliarity, is the cultural resistance of society, and this is a challenge in adopting a new strategy to net zero emissions.

Due to the substantial investment required for creating and purchasing "zero carbon" building products, altering developers' and end-users' attitudes and behaviours can be difficult. From the perspective of housebuilders, a hesitancy to deviate from conventional practices presents a significant obstacle to adopting NZCBs.

4.4. Technology

Technological advancements are essential for meeting NZCB standards, particularly in reducing operational carbon emissions. Besana and Tirelli [12] studied the NZCB target as achieved by utilising current technologies, but the options available to satisfy each performance criterion are restricted. Keeping up with and promoting new technologies that can help solve modern problems, especially in energy, sustainability, and building industries, is a hindrance between developed and developing countries.

Implementing design methods to evaluate buildings' performance and energy-efficient technologies leads to better construction techniques and materials, but it is also challenging.

4.5. Stakeholders engagement

Stakeholders play a crucial role in implementing net zero carbon buildings (NZCBs), particularly in addressing design and construction challenges [49]. For project-specific teamwork, it is crucial to identify and involve stakeholders during the design phases of the construction [92] and [78]. Effective stakeholder engagement is essential, and it must be ensured that all relevant stakeholders (policymakers, industry leaders, communities, etc.) are actively involved in the research, development, and application of new technologies or strategies.

Stakeholders must be engaged in formulating policies and regulations for net zero carbon to ensure they are feasible, effective, and aligned with practical needs. However, implementing the process from theory to practice would be a barrier. Collaboration should be tailored to specific projects or innovations, allowing stakeholders to work together toward targeted goals while sharing insights, resources, and risks.

4.6. Policy framework on net zero buildings

Policies and regulations are essential in boosting the demand for NZCB, as they can influence and direct public and stakeholder behaviours and practices toward achieving "zero carbon."[93,94] Policies and regulations have the potential to shape public opinion and steer stakeholder actions towards NZCBs [25].

4.6.1. International policy approaches

Various countries have adopted unique policy approaches to promote NZCBs, demonstrating the importance of tailored strategies:

According to the World Green Building Council status, local, regional, and national governments are actively creating policies and programs to encourage and regulate net-zero buildings in Germany. German Sustainable Building Council (DGNB) is developing a recognition program for buildings achieving net-zero carbon in operation and across lifecycle emissions. In France, the Alliance HQE-GBC has partnered with the government to develop a methodology and building label called E + C, which focuses on energy-positive and low-carbon buildings. This initiative aims to anticipate 2018–2020 environmental regulations and improve practices by integrating energy, environmental, and cost performance. Sweden embraced net-zero building concepts before formal certification. The Sweden Green Building Council is using certification to align early adopters and governments, promoting a unified approach to market clarity.

The UK policy mandates that all new homes be "zero carbon" by 2016 and non-domestic buildings by 2019, meaning they must achieve net zero carbon emissions throughout their operational lifetime. This policy promotes enhanced energy efficiency in building design to reduce energy consumption by occupants, particularly in heating and lighting, while also encouraging the use of on-site or off-site renewable energy sources to meet the remaining energy requirements [95].

These international approaches highlight the diversity of strategies used to advance NZCB goals and the necessity of aligning national policies with global sustainability objectives.

4.6.2. Key elements for a policy framework to achieve net zero buildings

A well-structured policy framework is crucial for achieving net zero buildings. Policymakers must develop strategies that expedite the transition to net zero, thereby playing a vital role in advancing global sustainability and climate objectives. The key elements that should guide the creation of effective policies are:

- Governments must establish clear definitions and criteria for net zero buildings, including design codes and standards. These guidelines must be quantifiable, enforceable, and aligned with international sustainability goals. Building codes should gradually become more stringent to ensure all buildings eventually achieve net zero status, with new construction mandated to meet these energy standards by a specified deadline.
- Financial incentives, such as tax credits, grants, low-interest loans, and rebates, should be introduced to encourage the construction of new net zero buildings and the retrofitting of existing ones. These incentives will help alleviate upfront costs, making sustainable building practices more economically feasible for developers and homeowners.
- To foster technological innovation, support for research and development in energy-efficient building technologies is necessary. This includes advancements in insulation materials, smart energy systems, and renewable energy solutions like solar power and geothermal heating. Government backing and collaborations with private sector innovators should be promoted to accelerate technological progress.
- Creating collaborative platforms is also essential, allowing architects, engineers, developers, policymakers, and utility companies to share insights, establish best practices, and address the challenges of scaling net zero technologies.
- Public education and awareness campaigns should emphasise the benefits of net zero buildings, such as long-term financial savings, environmental advantages, and improvements in health and comfort. These campaigns will help increase public demand and acceptance of sustainable building practices.
- Finally, a system should be established for continuous monitoring and reporting of energy use and carbon emissions in buildings. This will ensure compliance with net zero standards over time and enable data-driven policy adjustments as needed.

5. Recommendations for future research

According to the knowledge gaps that hinder the implementation of decarbonisation in the building environment, the following recommendations are proposed for future research with Net Zero Carbon buildings.

- Technology research on localised low-carbon materials and energy-efficient ways depending on location such as passive solar design, tailored to the specific conditions of each country. Legislation to mandate net zero building practices and the enforcement of comprehensive greenhouse gas (GHG) reduction strategies. Therefore, Best practices of net zero buildings need to be transferable between the countries. Additionally, research on region-specific low-carbon building materials and energy-efficient technologies is essential. This includes enhancing passive solar design methods, improving building insulation tailored to local climates, and exploring renewable energy systems that align with regional resources (e.g., solar, wind, geothermal).
- Further innovation is needed regarding the durability, recyclability, and carbon sequestration potential of low-carbon materials such as Cross-Laminated Timber (CLT), highly sulphated calcium silicate cement (HSCSC), and perovskite solar cells, particularly in terms of improving energy efficiency.
- The effectiveness of policies that mandate net zero carbon standards for all new buildings needs to be studied, with particular attention given to enforcement mechanisms for comprehensive greenhouse gas (GHG) reduction strategies. Additionally, continuous monitoring systems should be incorporated to ensure long-term adherence to net zero goals.
- Research should examine the potential benefits of introducing financial mechanisms, such as tax credits, grants, low-interest loans, and rebates, to encourage sustainable building practices and alleviate the burden of high upfront costs.

- Studies focused on raising awareness through national-level public education campaigns and policy-driven awareness programmes are critical to accelerating the adoption of net zero practices among the public.
- To facilitate the transfer of best practices, comparative studies between developed and developing countries should be conducted to identify scalable and replicable net zero solutions.

6. Conclusion

This study contributes to the evolving discourse to accomplish zero-emission buildings by synthesising current knowledge, identifying gaps, and recommending avenues for future research and practical implementation. Integrating comprehensive lifecycle assessments and innovative technologies, and advanced building materials are crucial in meeting global carbon reduction targets and mitigating the impact of buildings on climate change. Despite notable advancements in understanding NZCB strategies, significant research and practical efforts are required to address several research gaps and challenges across diverse building types, lifecycle stages, and regional contexts. Effective policies can influence public behaviour and stakeholder practices, fostering demand for sustainable construction. Comprehensive policy frameworks should include clear definitions, financial incentives, technological support, and stringent enforcement mechanisms. Moreover, Continuous monitoring, adaptive policies, and collaborative efforts will be essential for achieving long-term sustainability goals.

Moving forward, future research should focus on bridging knowledge gaps, particularly in developing countries, and exploring scalable best practices for NZCBs. Comparative studies between developed and developing nations can help identify transferable strategies.

In conclusion, achieving NZCBs will require continued innovation, supportive policies, and collaborative efforts across all sectors of society. By addressing the challenges and seizing the opportunities within the NZCB environment, stakeholders can pave the way for a sustainable future, ensuring that buildings not only meet functional needs but also contribute to global sustainability and climate objectives.

CRediT authorship contribution statement

Nwe Ni Myint: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Muhammad Shafique:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xiangming Zhou:** Writing – review & editing, Conceptualization. **Zhuang Zheng:** Writing – review & editing, Methodology, Data curation, 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.

Data availability

Data will be made available on request.

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