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Review

Zero-carbon building materials in New Zealand context: a systematic literature review

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Received: 26 August 2024 / Accepted: 4 February 2025
Published online: 26 May 2025

Abstract
The transition towards zero-carbon building materials represents a critical pathway for mitigating carbon emissions in the construction sector. Utilising recycled materials in construction offers many benefits, most of which are resource conservation. This natural resource conservation helps mitigate environmental degradation and preserve delicate ecosystems. As such, this study aimed to identify the most suitable zero-carbon construction materials for use within New Zealand's building sector by systematically reviewing the literature focusing on wood, rammed earth and strawbale materials. To explore the effectiveness of each material, six primary factors have been identified such as sustainability, cost-efficiency, longevity, visual attractiveness, energy conservation, and ecological ramifications. Therefore, 1808 studies were found on Scopus, IEEE, and Google Scholar. Based on the inclusion and exclusion criteria in this study, the final 20 eligible studies published from 1999 to 2024 were reviewed. This study followed the PRISMA Statement to comprehensively explore the existing literature. Results highlighted that environmental factors such as moisture can directly influence the durability of these construction materials and structures. Although sustainability is often defined in terms of thermal behaviour and life cycle assessment, limited research addresses the aesthetic aspects and comprehensive economic implications of material choices. The findings demonstrate sufficient thermal properties of straw bales and the lower embodied energy of rammed earth compared to other traditional materials, emphasising their potential to enhance energy efficiency in construction. This study recommended future research, contributing valuable insights for stakeholders seeking eco-friendly building components in sustainable construction practices.

Article Highlights

- Wood, rammed earth, and straw bales show strong potential for zero-carbon construction.
- There were no studies found that explored the cost-effectiveness of timber, strawbale and rammed earth as zero-carbon materials, highlighting the need for further exploration
- The materials significantly reduce energy consumption and CO_2 emissions in building design

Keywords Zero-carbon buildings · Green materials · Wood · Rammed earth · Strawbales

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1 Introduction

The impact of climate change on the building sector is substantial. In New Zealand, buildings contribute directly and indirectly to approximately 16–20% of the country's total Greenhouse Gas (GHG) emissions [1]. Fraser-Jones, Morgan [2] indicate that the building and construction industry is responsible for 15.1% of New Zealand's overall emissions while [3] maintains that the construction sector produces 20% of NZ's Greenhouse Gas (GHG) emissions. The sector's substantial diesel fleet, concrete production, and management of building waste represent significant sources of emissions that require considerable investment and transformation. As such, the NZ government has committed to minimise its carbon dioxide emissions by 2050 in line with UN goals [4]. To achieve this, NZGBC [5] recommended that new buildings should be constructed with zero carbon and with 20% less embodied carbon by 2025. The BRANZ Transition to a zero-carbon built environment initiative aims to ensure that by 2050, the building and construction industry achieves the goal of delivering affordable net-zero carbon buildings [6].

The construction industry plays a critical role in climate change by adopting eco-friendly practices and materials [7, 8]. Many countries worldwide are increasingly prioritising the transition towards zero-carbon building materials to mitigate climate change impacts and promote sustainable building practices [9, 10]. Zero-carbon building materials are fundamental to reducing GHG emissions and offer several advantages, such as reduced environmental impact, carbon neutrality, energy efficiency, renewable and sustainable sourcing, and improved health and indoor air quality [11–13]. These materials are a fundamental component of sustainable construction, and the careful selection of available materials has prompted a growing interest in green alternatives [14].

Materials such as wood, rammed earth, and strawbale offer sustainability alternatives due to their renewability and versatility as construction materials. Such green materials have garnered significant attention as a building resource that aligns with ecological principles [15, 16]. These materials are sourced from renewable resources or recycled materials, reducing environmental degradation. They often have minimal or no net carbon emissions, contributing to climate change mitigation [17]. Additionally, they provide excellent insulation [18], lowering energy consumption [19] and operational costs [20]. Sourced sustainably, they promote long-term environmental responsibility [21]. Lastly, they emit fewer pollutants, enhancing indoor air quality and occupant health [22].

Zero-carbon materials hold immense promise for revolutionising the construction sector while significantly mitigating environmental impact [23]. By minimising or eliminating carbon emissions throughout their life cycle, these materials offer a sustainable alternative to traditional construction materials [24]. Their use can substantially reduce the carbon footprint of buildings [25], making a significant contribution to global efforts to combat climate change [26]. With their potential for durability and longevity, zero-carbon materials offer a pathway towards constructing resilient and environmentally responsible buildings for a sustainable future [27].

While the benefits of zero-carbon materials are evident, there remains a significant gap in comparing these materials based on critical features such as climate responsiveness, local availability, economic feasibility, and cultural appropriateness, particularly in the context of New Zealand's unique construction environment [7]. This lack of region-specific knowledge poses a challenge for stakeholders, as current guidance does not sufficiently support informed decision-making regarding which materials are most suitable for achieving zero-carbon goals in New Zealand's building sector [28]. Given New Zealand's distinct climatic conditions and its ambitious goal of achieving carbon neutrality by 2050 [29], identifying optimal zero-carbon materials is crucial. Moreover, as a country with a strong focus on sustainability, the relevance of selecting regionally appropriate, low-emission materials is heightened compared to other regions, where such practices may not be as advanced or emphasised [30].

This review seeks to identify the most suitable zero-carbon building materials for New Zealand's construction industry, focusing on wood, rammed earth, and strawbales. We assess these materials across six key criteria: sustainability, cost-effectiveness, durability, aesthetic appeal, energy efficiency, and environmental impact. By thoroughly evaluating and comparing these materials, our research contributes to filling a crucial knowledge gap in the region. The primary contribution of this study is to provide clear, evidence-based guidance for stakeholders, architects, and policymakers in the New Zealand construction sector, enabling them to make informed decisions that align with the country's zero-carbon goals and sustainable development targets.

2 Background

The concept of Zero Carbon Buildings (ZCB), often synonymous with Net-Zero Energy Buildings (NZEB), goes beyond mere energy efficiency [30, 31]. It represents a holistic and ambitious effort to minimise the carbon footprint associated with a building's entire life cycle, encompassing design, construction, operation, and eventual decommissioning [32]. Achieving such a commendable goal demands innovative design strategies, advanced technological integration, and a commitment to sustainable practices throughout the building's lifespan [33]. As the urgency to address climate change intensifies, the importance of zero-carbon buildings becomes increasingly evident. These structures contribute significantly to global efforts to curb carbon emissions and serve as beacons of innovation, showcasing the potential for harmonious coexistence between the built environment and the natural world [34].

2.1 Building materials: wood, rammed earth, and strawbale

Wood, rammed earth, and strawbale offer numerous benefits as building materials, contributing to sustainable construction practices and environmental stewardship [35]. Firstly, wood is renewable, readily available, and boasts excellent thermal properties, providing effective insulation and reducing energy consumption for heating and cooling [36]. Its versatility allows for various construction techniques, from traditional timber framing to modern engineered wood products, catering to diverse architectural styles and design preferences. Additionally, wood sequesters carbon dioxide (CO_2) throughout its life cycle, acting as a carbon sink and mitigating greenhouse gas emissions. Moreover, wood construction supports local economies and forestry industries, fostering economic growth and job creation in communities [37].

Similarly, rammed earth construction utilises locally available soil, minimising transportation and resource depletion associated with traditional building materials [38]. Rammed earth buildings exhibit exceptional durability and thermal mass, regulating indoor temperatures and reducing the need for mechanical heating and cooling systems [39]. This results in energy savings and lower operational costs over the structure's lifespan. Additionally, rammed earth structures offer aesthetic appeal and architectural diversity, blending harmoniously with natural landscapes and cultural contexts. Furthermore, the use of rammed earth promotes sustainable land management practices and soil conservation, enhancing ecosystem resilience and biodiversity [40].

Strawbale, often considered a byproduct of agricultural activities, offers a sustainable insulation and wall construction alternative. Strawbale buildings boast excellent thermal performance, providing superior insulation compared to conventional materials [16]. This contributes to energy efficiency and occupant comfort, creating healthier indoor environments with stable temperatures year-round. Additionally, straw bales are renewable, biodegradable, and locally sourced, reducing reliance on fossil fuels and minimising environmental impact [41]. Moreover, straw bale construction supports rural economies and agricultural communities, providing additional revenue streams for farmers and promoting sustainable agricultural practices. Overall, wood, rammed earth, and straw bales offer multifaceted benefits as building materials, aligning with principles of sustainability, resilience, and environmental responsibility [42].

These materials were chosen for this review due to their significant contributions toward achieving Zero Carbon Buildings (ZCBs) and their alignment with sustainable construction practices [43–45]. These materials provide substantial environmental benefits that help mitigate climate change by reducing greenhouse gas emissions and improving energy efficiency. Wood, for example, not only offers renewable and readily available resources but also sequesters carbon dioxide (CO_2) throughout its life cycle, making it a key material for lowering a building's overall carbon footprint [46]. Its excellent thermal properties contribute to energy savings in heating and cooling, directly supporting ZCB goals by reducing operational energy use. Wood's versatility also promotes local economic growth, furthering the sustainable development agenda [8].

Similarly, rammed earth utilises locally available soil, reducing the embodied carbon typically associated with long-distance material transportation [47]. Its thermal mass properties reduce reliance on mechanical systems for heating and cooling, enhancing energy efficiency and lowering operational costs over the building's lifespan. Rammed earth construction supports the ZCB framework by using natural, low-carbon materials that contribute to durable and energy-efficient structures [48]. Strawbales, on the other hand, often a byproduct of agriculture, offer an eco-friendly insulation alternative. With superior thermal performance, straw bale construction enhances energy efficiency, contributing to the overall reduction of operational emissions [49]. Being renewable, biodegradable, and locally sourced, straw bales further align with the goals of ZCBs, minimising the environmental impact of construction while supporting rural economies and sustainable farming practices [50].

3 Materials and methods

3.1 Formulating the research questions

This review aims to compare the viability of suitable zero-carbon building materials for application in the New Zealand construction industry. Based on a previous study Hashemi Araghi, Rasheed [51], three zero-carbon materials, namely wood, rammed earth, and strawbale, were identified as the most suitable for New Zealand. We examined these materials across various factors such as sustainability, cost-effectiveness, durability, aesthetic appeal, energy efficiency, and environmental impact, specifically focusing on.

3.2 Identifying the relevant studies

This research used a systematic literature review methodology guided by the Preferred Reporting Items for Systematic Reviews (PRISMA) Statement [52]. The systematic approach ensures a rigorous and transparent process in identifying, selecting, and synthesising relevant literature published in New Zealand about zero-carbon buildings and the associated green materials, including wood, rammed earth, and straw bales. Adhering to the PRISMA guidelines enhances the quality and reliability of the review, providing a structured framework for the systematic analysis of research findings [53]. By incorporating the PRISMA Statement, this paper seeks to uphold methodological rigour, transparency, and reproducibility, thereby strengthening the credibility of the systematic literature review and the validity of the insights gleaned from the synthesis of existing knowledge.

In pursuing a comprehensive and well-rounded exploration of the existing literature, this research harnessed the search capabilities of three prominent databases: Scopus, Google Scholar, and IEEE Xplore. These databases were selected to ensure a thorough and exhaustive review, encompassing various scholarly articles, conference proceedings, and research papers [54, 55]. By incorporating Scopus, Google Scholar, and IEEE Xplore into the search strategy, the study aimed to access a broad spectrum of academic sources, enhancing the depth and inclusivity of the systematic literature review. Utilising these reputable databases reflects a commitment to a robust and methodologically sound exploration of the current knowledge landscape in sustainable construction practices.

Scopus is a comprehensive abstract and citation database of peer-reviewed literature [56]. It covers various disciplines, including science, technology, medicine, social sciences, and arts and humanities. Scopus provides access to many scholarly journals, conference proceedings, and patents. Its advanced search features and citation analysis tools make it a valuable resource for researchers seeking multidisciplinary information [57].

Google Scholar is a freely accessible search engine that indexes scholarly articles, theses, books, conference papers, and patents. It covers a broad spectrum of academic disciplines and is widely used for its user-friendly interface and inclusivity. Google Scholar provides a convenient way to explore scholarly literature across various sources, making it a popular tool for researchers, students, and academics. IEEE Xplore is a digital library and database specifically focused on content related to electrical engineering, computer science, and electronics. It includes a vast collection of IEEE (Institute of Electrical and Electronics Engineers) journals, conferences, and standards [58]. IEEE Xplore is a key resource for researchers and professionals in the fields of technology and engineering, offering a specialised repository of cutting-edge research and technological advancements. Table 1 provides the eligibility criteria for selecting the studies.

The search keywords used in this study are formulated as follows: "Zero Carbon" AND construction OR building* AND "New Zealand". The search strategy utilises the AND and OR field operators to comprehensively explore relevant literature. Besides, to ensure comprehensive coverage of relevant studies, this research employs the backward and forward snowballing technique [59]. This involves tracing citations backwards to earlier works (backwards snowballing) and exploring subsequent references citing the primary studies (forward snowballing), enhancing the inclusiveness of the literature review [60]. Consequently, 20 papers are identified. Figure 1 illustrates the PRISMA Framework in this study.

According to the Fig. 1, the studies undergone three different stages of selection such as identification, screening, and include. For each stage, there are some inclusion and exclusion criteria, which formulated based on the research

Table 1 The screening stages and criteria to select eligible studies

Stage	Criteria	Decision
Before screening	Not written in English	Exclusion
	Not a journal article	Exclusion
	If the study is a conference paper, book chapter, or a review paper	Exclusion
	When the specified keywords are present either in the entirety or at least within the title, keywords, or abstract of the paper	Inclusion
Initial screening	Studies provide sufficient information on the subject matter	Inclusion
	Studies that assessed or evaluated the materials	Inclusion
	Studies used experiment or simulation analysis the materials	Inclusion
	Studies must be directly relevant to the topic of interest within the scope of the research	Inclusion
Full-text manual screening	There was no experiment or simulation results	Exclusion

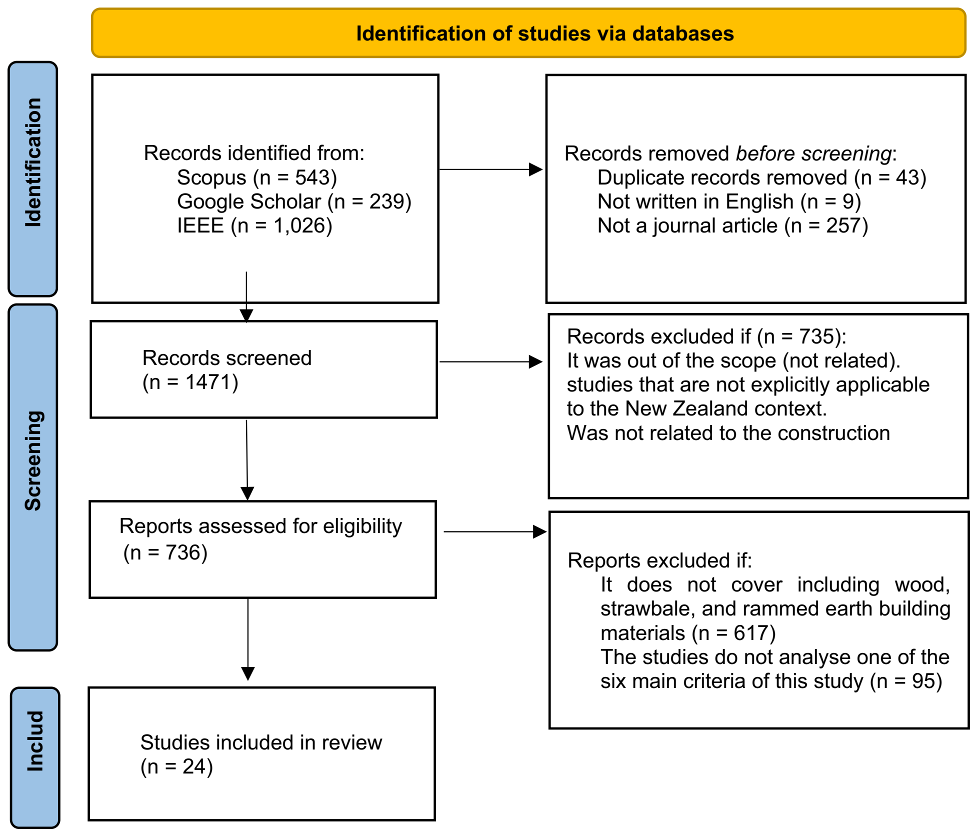


Fig. 1 Identification of relevant studies via PRISMA Flow Diagram

aim and scope to refine our results. Consequently, the last stage showed that how many studies are relevant to full-text manual screening.

4 Results

4.1 General overview

In this systematic literature review, we identified 24 papers published between 1999 and 2024, including 21 journal articles and 3 conference papers. Figure 2 illustrates the number of publications and types of scholarly outputs per annum.

The selected studies have employed various methodologies for data collection and analysis of these building materials. Among them, twelve studies utilised experimental measurements as a primary means of gathering data.

Fig. 2 Overview of the scholarly outputs of the selected studies

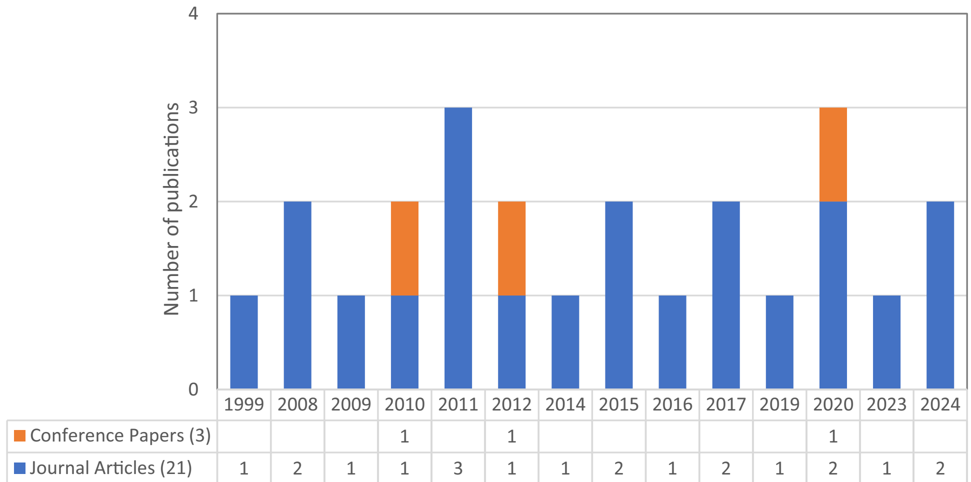
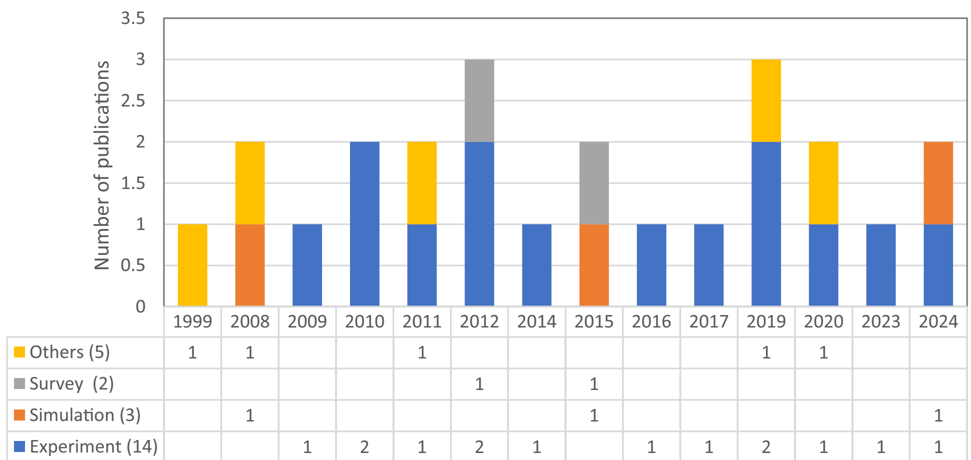


Fig. 3 Summary of the methodologies utilised in the selected studies



Three studies employed simulation software, demonstrating a reliance on computational modelling for analysis. Additionally, two studies relied on survey methodologies, focusing on gathering qualitative or quantitative data directly from participants. For the survey, the studies used a survey to get participant feedback and a questionnaire to collect subjective information. Beyond these primary approaches, 5 studies employed other methods. Here, we categorised Laboratory measurements [61, 62], Field measurements [61], and Stereo-photogrammetry [63] as experimental methods. However, for the category "Others", papers used review analysis [36], a comparative study [64], and CORRIM assessment: Life Cycle Inventories [65]. Figure 3 provides further details on this.

This research aims to identify the potential impact of the target materials on 6 themes which are: These themes include:

- Durability, which examines the longevity and resilience of building materials and structures.
- Thermal performance, which assesses the ability of buildings to maintain comfortable temperatures and minimise energy consumption.
- Insulation, which focuses on materials and techniques for reducing heat transfer and improving sound insulation.
- Aesthetics, which considers the visual appeal and design elements of buildings.
- Energy performance, which evaluates the overall energy efficiency and consumption of buildings.
- Co_2 emission, which addresses the environmental impact of building materials and processes in terms of carbon dioxide emissions.
- Cost, which analyses the economic implications of various building strategies and materials.
- Environmental impact encompasses broader considerations of the ecological consequences of building design and construction.

Table 2 The frequency of topic/theme occurrence among the eligible articles

Sources	The research theme				
	Cost-effectiveness	Durability	Aesthetic appeal	Energy efficiency	Environmental impact
[66]				×	
[61]		×		×	
[67]				×	×
[64]					×
[68]		×			
[69]		×			
[70]					
[36]		×			
[71]			×	×	
[72]		×			×
[63]		×			
[73]				×	
[65]				×	
[74]					×
[75]		×			
[62]		×		×	
[76]				×	
[77]				×	
[78]		×		×	
[79]				×	
[80]		×			
[81]		×			
[82]		×			
[83]				×	
Total	0	12	1	12	5

These themes collectively highlight the multidimensional nature of research in the field, emphasising the importance of addressing practical and environmental concerns in building practices. Table 2 summarises the main themes of this study, indicating which studies focused on each theme to highlight the areas that have been most extensively explored. We achieved this by highlighting the themes and providing a summary of the total occurrences at the end.

4.2 Durability of materials

New Zealand's climatic conditions are dominated by persistent environmental factors, which are responsible for the lifespan of the materials. Rammed earth favours well in New Zealand weather conditions as unstabilised rammed earth walls can experience erosion rates of approximately 1 mm/year over 20 years of natural weathering (Umubyeyi, Wenger [66], without significant deterioration. A study showed that the estimated lifespan of the freestanding unstabilised rammed earth wall with minimal protection from natural climatic conditions in a temperate climate is between 37 and 75 years. Swan, Rteil [36], in their study, found that in areas that experience up to 635 mm (25 in.) of rain per year, unstabilised earthen walls left unprotected are likely to erode at a rate of 25.4 mm (1 in.) in 20 years on vertical surfaces and 50–75 mm (2–3 in.) per year on horizontal surfaces.

Bui, Morel [63] studied the durability of rammed earth walls exposed for 20 years to natural weathering. They found that none of the walls collapsed completely during the 20-year period despite being on-site exposed to the weather for over 100 years. In a specific study context with a precipitation annual of about 1000 mm, the erosion measurement of unsterilised rammed earth walls after 20 years of exposure was about 6.4 mm, corresponding to 1.6% of wall thickness. This erosion led to an extrapolated lifetime longer than 60 years, indicating potential durability.

Also, Kariyawasam and Jayasinghe [67] focused on assessing the strength and durability of Cement Stabilized Rammed Earth (CSRE) as a sustainable construction material. Compressive and flexural strength tests on CSRE wall panels with different cement contents demonstrated satisfactory results, meeting Earth Building standards. The material exhibited lower embodied energy than traditional burnt clay bricks, contributing to sustainable construction practices. CSRE has been successfully applied in various construction projects, showcasing its strength, durability, and cost-effectiveness, making it a promising alternative for environmentally friendly building practices.

Moisture is a significant environmental factor affecting the durability of construction materials and structures. Strawbales are highly susceptible to high-moisture environments. This is because, in high-moisture environments, the proliferation of fungi and bacteria responsible for straw deterioration occurs within an optimal temperature range of 20–70°C, with survival below 10°C being unlikely (D'Alessandro, Bianchi [61]. Moisture content evaluation is crucial for assessing the durability of straw bale buildings, with values below 20% preventing decomposition and deterioration typically starting at moisture content levels of 25–30% [68].

That said, Strawbale has its positive features when exposed to environmental factors. For instance, Thomson and Walker [69] conducted a durability assessment on the resilience of straw bales exposed to high humidity levels. The findings indicated an initial rapid growth of CO_2, which ceased after 10 days. Observations revealed no significant decay in three-year-old straw bales exposed to 87% relative humidity. These insights suggest that straw bale construction can be durable under certain conditions. In the study by Ashour, Georg [62], the researchers observed that temperature decreases over time in a manner that can be mathematically described by an exponential equation. The strength of this relationship is quantified by a correlation coefficient of approximately 80.05%, indicating a strong correlation between time and the decrease in temperature.

Additionally, the relative humidity in the straw bales increased exponentially with time, showing a correlation of 94.04% (relationship between time and the increase in relative humidity in the straw bales). Notably, the results highlighted the exceptional insulation properties of straw materials against external relative humidity, attributed to their low moisture content. Mechanical tests indicated higher strength in vertical orientation, and deformation modulus was evaluated for horizontal and vertical bales. Furthermore, the study demonstrated stable temperature and relative humidity distribution within the straw walls, with slow moisture migration observed. Overall, the findings underscored straw's durability and decay resistance as a building material, with a measured pH value inside the bales of 7.29. Table 3 shows the final summary of the durability of the durability performance of the target materials.

However, three studies explored the durability of wood or wood-based construction materials mostly on moisture and mould growth. The findings of Nofal and Kumaran [70] regarding wood decay and durability include the development of a wood-rotting model specific to wood-based materials, calculating the impact of operating conditions on building envelope service life and identifying loss in strength and microstructural changes due to wood-rotting fungi. The study also discusses the damage variation caused by fungi under different air leakage conditions and the progress of fungal decay in wood samples exposed to outdoor weather conditions. Additionally, the research highlights the importance of understanding deterioration mechanisms under fungal attacks and the need for further studies to identify potentially harmful wood-decay fungi in different environments. The study proposes a relationship to estimate the percentage of viable spores in terms of multiples of the dry period time, with the equation $VS = 2.258e^{(-0.7548N)}$. This relationship helps understand the impact of viable spores on damage rate under wet conditions after a drying period. Also, the study reveals that mould growth increases with higher air leakage rates, but damage decreases as the wall dries due to mould being a surface phenomenon. Figure 4 illustrates the optimal conditions for mould growth and the impact of air leakage on wood-rot damage provided by [70].

The results of the study by Singh, Page [71] indicated that laminated veneer lumber samples exhibited minimal mycelium growth and localised decay near feeder blocks after 6 months, contrasting with untreated solid wood samples that showed extensive mycelium growth and severe decay. Leaching increased moisture content in oriented strand board samples, leading to mould growth. Boron treatment effectively prevented decay in cross-laminated timber samples, irrespective of leaching, highlighting the susceptibility of untreated oriented strand board and cross-laminated timber to biodegradation. These findings underscore the need for further research to enhance the durability of wooden panels in construction applications. After 6 months of exposure, it was observed that differences in decay development were evident among the various wood products tested. Untreated solid wood exhibited severe decay, while laminated veneer lumber samples showed minimal mycelium growth and localised decay. This suggests that the duration of exposure to environmental conditions may influence the extent of decay in different wood materials.

Kallavus, Järv [72] explored the vulnerability of environmentally friendly wood-based panels to surface mould growth in conducive moisture conditions. Testing was conducted in a laboratory using a modified method that omitted sterilisation and oven-drying of samples. The findings underscored the risks associated with surface mould growth on construction materials, emphasising the significance of appropriate handling to avert spoilage and potential health hazards. The key findings regarding moisture and durability in relation to mould growth on wood-based construction materials indicate that these materials are highly susceptible to surface mould development in environments with elevated moisture

Table 3 Finalizing the summary of the selected studies on durability

Study	Focus	Properties
[61]	Durability of straw in high moisture environments	Fungi and bacteria thrive at 20–70°C; survival below 10°C is unlikely. Moisture below 20% prevents decomposition; deterioration starts at 25–30% moisture content
[66]	Erosion of unstabilised rammed earth walls	Erosion rate is about 1 mm/year over 20 years. Lifespan is estimated between 37 and 75 years in a temperate climate
[36]	Rain effects on erosion of unstabilised earthen walls	The erosion rate is 25.4 mm in 20 years for vertical surfaces and 50–75 mm per year for horizontal surfaces in areas with up to 635 mm of rain annually
[80]	Consumer preferences for building materials	The complex interplay of durability perceptions, environmental attitudes, knowledge, and past experiences influence preferences, with a trend towards stone or bricks over wood
[63]	The durability of rammed earth walls exposed to natural weathering	No complete collapse after 20 years; erosion of 6.4 mm after 20 years with a lifespan of over 60 years
[69]	Durability of straw bales in high humidity	Initial CO_2 growth ceased after 10 days; no significant decay in the three-year-old straw at 87% RH
[62]	Insulation properties and durability of straw bales	Exponential decrease in temperature, exponential increase in relative humidity, high insulation properties, slow moisture migration, and pH value of 7.29
[67]	Strength and durability of Cement Stabilized Rammed Earth (CSRE)	CSRE met Earth Building standards, showed lower embodied energy, and demonstrated strength and durability suitable for sustainable construction

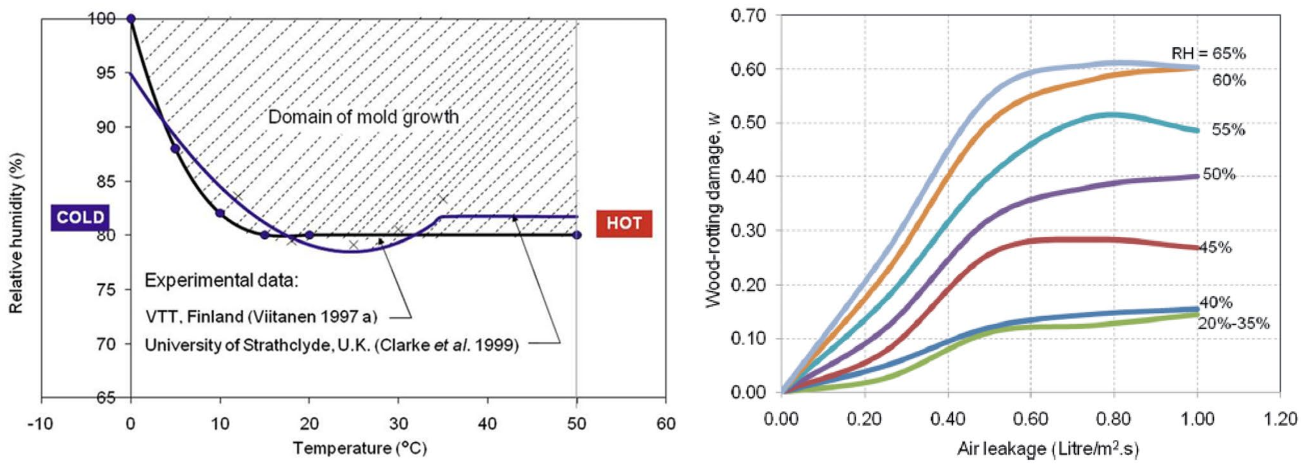


Fig. 4 Conditions promoting mould fungi growth due to optimal moisture and temperature levels (left) and the impact of air leakage rates on the extent of wood-rot damage (right) [70]

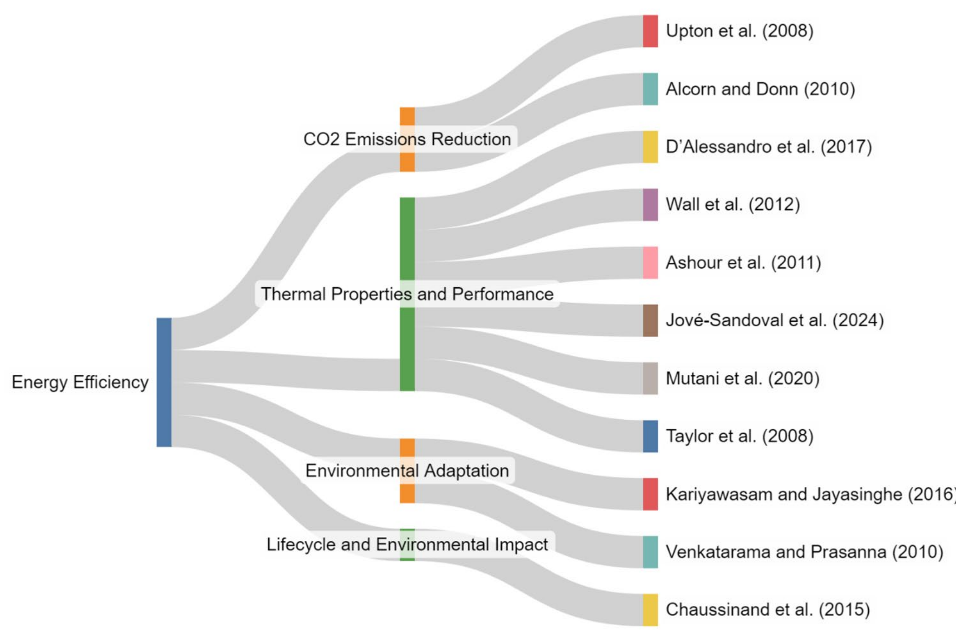


Fig. 5 The themes derived from studies related to energy efficiency are categorised based on commonly used terms within the relevant literature

levels. Improper handling, such as delays in construction processes and inadequate storage, can lead to significant mould proliferation. The presence of moisture and organic material, along with exposure to mould spores from the air, are critical factors contributing to mould growth on these materials. The relationship between durability and time in the context of mould growth on wood-based construction materials suggests that prolonged exposure to moisture over time can compromise the durability of these materials. As time progresses, the likelihood of mould development increases, especially if the materials are not stored or handled properly. The longer the materials are exposed to moisture, the greater the risk of surface mould growth, potentially leading to deterioration and reduced longevity of the wood-based panels.

4.3 Energy efficiency

Notably, due to the common terms they have used in their work, the research team combined the theme 'sustainability' in this category. Thus, eleven studies focused on the target materials' energy efficiency and thermal behaviour. Figure 5 shows the themes derived from studies on energy efficiency, which are classified according to the prevailing terminology found in relevant literature.

Energy efficiency is one of the key factors influencing the selection of zero carbon materials and makes strawbale, wood and rammed earth favourable amongst other construction materials. For instance, Alcorn and Donn [73] show that using materials like strawbale and timber in construction can significantly reduce energy consumption and CO_2 emissions. The thermal properties of straw bales, with comparable thermal conductivity to high-insulation materials, make them a viable and sustainable option for construction projects.

The study of D'Alessandro, Bianchi [61] investigated the thermal conductivity of straw bales using a guarded hot plate apparatus and compared the results with in-situ measurements. The thermal transmittance values obtained align well with commercial earthen plaster and straw bale thermal conductivity data. The research emphasises the importance of accurate thermal performance assessments for sustainable building materials like straw bales. They found that the embodied energy of straw bale walls accounts for 6% of the total, with the wooden frame being the most impactful component at 54%. The use phase of the building, particularly electricity consumption, contributes to about 92% of the whole life cycle impact in terms of global warming potential. Straw bale production is the major contributor to CO_2 equivalent emissions at 47%, highlighting the significance of material selection in sustainable construction practices.

Wall, Walker [74] discussed constructing and testing a prototype house made of prefabricated straw bale panels with softwood timber frames and lime renderings. The air permeability of the house met UK Building Regulations standards. Thermal surveys were conducted to assess energy efficiency, with findings showing minimal heat loss and uniform temperatures across the panels. Fire resistance and sound insulation tests were also performed, exceeding regulatory requirements. Another study done by Taylor, Fuller [75] assessed the evaluation of a rammed-earth building in terms of thermal comfort and energy use. Findings revealed that the building faced challenges with excessive heat in summer and cold in winter, leading to discomfort among occupants. High energy consumption for heating was identified, prompting simulations to propose design and control modifications for improved efficiency. The study highlights the struggle to maintain thermal comfort while reducing energy consumption, emphasising the need for enhancements in building design and operational strategies.

Jové-Sandoval, García-Baños [76] investigated the energy and thermal behaviour of boards and adobe walls with natural fibres. The insulation properties were enhanced by incorporating agro wastes like wheat straw fibres, reducing thermal conductivity. Boards exhibited lower thermal transmittance than adobes, suggesting the potential for energy-efficient building materials. The study found that incorporating natural fibres like wheat straw significantly reduced thermal conductivity, with up to 60% observed improvements. Additionally, boards showed a considerable decrease in thermal transmittance compared to adobe walls, with reductions of around 50% achieved. The energy performance of the straw bales was demonstrated by a study performed by Ashour, Georg [62], wherein they evidenced the ability to maintain stable temperature levels within the walls, indicating efficient insulation properties that can help reduce heat loss in buildings. The study also emphasised the impact of external conditions on the thermal stability of the bales, highlighting their potential to contribute to energy efficiency in construction. The results underscored the importance of straw bales as a renewable and sustainable building material that can effectively regulate temperature and enhance energy conservation in structures.

Rammed earth's energy efficiency is well noted, especially when combined with other materials. For example, Kariyawasam and Jayasinghe [67] assessed the energy efficiency of cement-stabilised rammed earth (CSRE) and showed that CSRE has lower embodied energy than traditional materials like burnt clay brick masonry. The embodied energy of CSRE walls was found to be 15–25% of burnt clay brick masonry, making it a more sustainable option. Additionally, CSRE has demonstrated better thermal comfort performance, with approximately a 3°C reduction in indoor temperature compared to cement block walls, leading to lower energy demand for maintaining comfortable buildings [67]. Venkatarama Reddy and Prasanna Kumar [77] also studied cement-stabilised rammed earth walls and revealed that the compaction energy input varies with the clay fraction in the soil mix and is sensitive to the density of the walls. The compaction energy ranged from 0.033 MJ/m3 to 0.36 MJ/m3 for different densities and cement contents. It was found that the energy expended during compaction is minimal compared to the energy content of cement. Additionally, the total embodied energy in the walls increased linearly with higher cement content, ranging from 0.4 to 0.5 GJ/m3 for cement content between 6 and 8%.

For wood, the study results of Upton, Miner [65] indicated that wood-based construction materials have lower embodied energy and CO_2 emissions compared to concrete, steel, or brick systems in residential buildings with comparable thermal performance. The embodied energy in residential construction materials ranges between 0.5 and 1 EJ year^-1 (exajoules per year), with embodied CO_2 emissions between 30 and 60 million tonnes (Mt) year^-1. Wood-based wall systems consistently show lower energy and emissions impacts, significantly reducing non-renewable energy use in the residential sector.

Chaussinand, Scartezzini [78] focused on analysing the thermal behaviour and energy performance of a straw bale building in Switzerland. The research aimed to understand the building's energy consumption and environmental impact by creating a thermal-dynamic model and conducting a life cycle assessment. The findings revealed that the straw bale construction exhibited low heat capacity, leading to overheating challenges in summer, which could be mitigated by managing solar gains and using external blinds. Despite these challenges, the ECO46 building showcased efficient energy consumption, surpassing standard buildings, and demonstrated sustainability using solar panels, ventilation systems, and insulation. Overall, the study concluded that straw bale buildings could offer a sustainable alternative in construction due to their low embodied energy and favourable thermal performance. The study showed that the ECO46 building consumes less than 10% of the energy consumed by a standard office building, highlighting its excellent energy performance for heating compared to most Swiss administrative buildings. Additionally, the discomfort rate due to overheating in occupied rooms ranged from 3.7% to 12.1%, considered good compared to the ASHRAE 14–2002 Guide's criteria of below 10%.

Mutani, Azzolino [79] focused on evaluating the energy and thermal behaviour of two different buildings, Casa Cembo and a pre-assembled prototype constructed with straw walls. Thermal conductance measurements were conducted in homogeneous areas exposed to the north to avoid incident solar radiation issues. Results showed that Casa Cembo met the Ulim limits set by Italian regulations, while the pre-assembled prototype exhibited higher heat dispersion and did not meet the Ulim limits due to potential transport issues with the straw. The dynamic characteristics of the straw walls were analysed, showing differences in thermal performance between the two case studies. A good result in the study was defined as thermal conductance not deviating by more than ± 5% from the value obtained 24 h before over a period of more than 72 h. The analysis revealed that Casa Cembo demonstrated very good results, meeting the Ulim limits set by Italian regulations. In contrast, the pre-assembled prototype showed higher heat dispersion and did not meet the Ulim limits due to potential transport issues with the straw.

4.4 Environmental impact

Only two studies focused on the environmental impact of the materials. The results of Høibø, Hansen [80] discusses various aspects of building material preferences in urban housing, focusing specifically on wood and its environmental impacts compared to other materials. They highlighted that the timber-framed buildings generally have a lower global warming potential than concrete and steel structures. This makes wood a more positive option from a carbon perspective. the findings emphasize that wood is perceived as an environmentally friendly alternative to conventional building materials, particularly in the context of sustainability and carbon footprint reduction. Alcorn and Donn [73] concluded that using materials like strawbale insulation and timber framing can significantly reduce CO_2 emissions due to their carbon sequestration properties. Both strawbale and timber are highly effective at sequestering carbon, thus reducing CO2-equivalent (CO2-e) emissions in house construction. For example, using strawbale insulation in walls, floors, and ceilings can reduce CO2-e emissions by up to 29%. The study found that strawbale and timber significantly reduce CO2 emissions by absorbing carbon throughout their life cycle, whereas materials like concrete and polystyrene contribute to higher emissions.

5 Discussion

We found 24 studies published between 1999 and 2024, among them 3 conference papers and 21 journal articles. Notably, no studies have investigated the cost-effectiveness of the target materials in their respective research endeavours. We also consolidated studies that focused on both 'sustainability' and 'energy efficiency' due to their overlapping topics and the use of shared terminology. According to the studies, we identified two additional themes, namely 'thermal comfort' and 'insulation', frequently addressed due to their significant focus in the literature. Figure 6 illustrates the repetition rate of each topic/theme in the studies.

While the study by Yan, Shi [81] provides valuable insights into the economic implications of material choices, it stands alone among the selected studies in addressing this aspect comprehensively. The dominance of wood and wood products

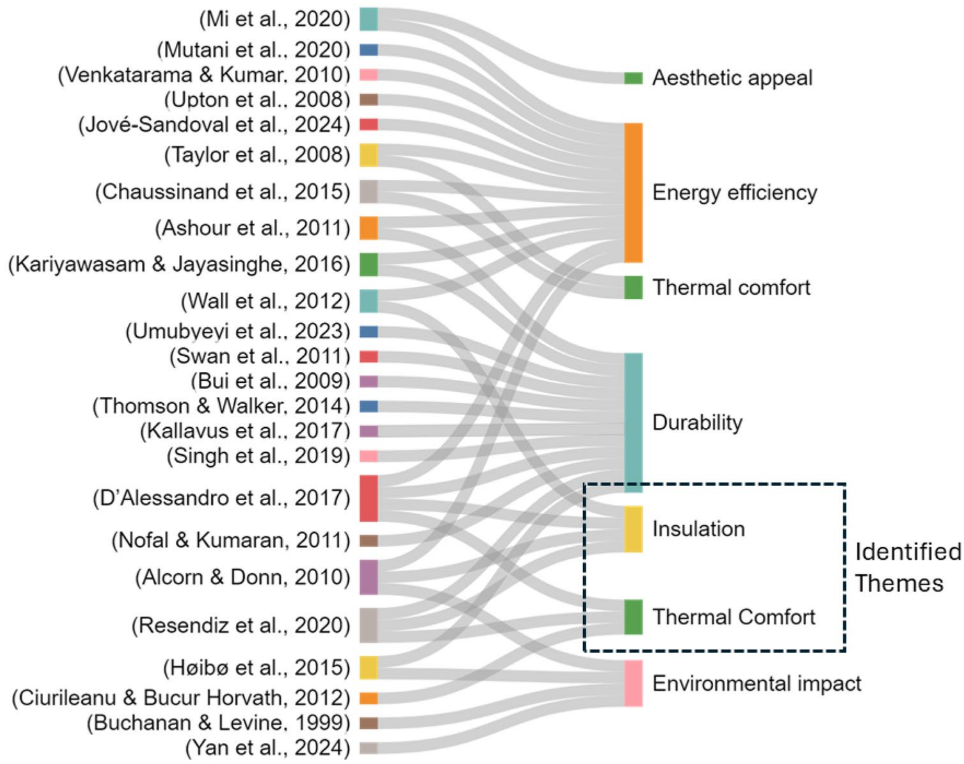


Fig. 6 The frequency of topic/theme occurrence among the eligible articles

in construction expenses highlights the need for further exploration into cost-effective alternatives, especially considering the increasing demand for sustainable building materials. Future research should aim to conduct more comprehensive cost–benefit analyses, considering not only material costs but also long-term maintenance and operational expenses to provide a holistic understanding of cost-effectiveness in sustainable construction.

Regarding durability, the selected studies offer valuable insights into the factors influencing the lifespan and resilience of construction materials. From the impact of environmental conditions on unsterilised rammed earth walls to the decay resistance of straw bales and the strength of cement, there remains a need for further research to standardise durability assessment methodologies and expand the scope of the investigation to include emerging sustainable materials. Future studies could explore the synergistic effects of combining different materials for enhanced durability and resilience and investigate novel materials and construction techniques to address durability challenges in sustainable construction. The study Bui, Morel [63] examined rammed earth walls over a 20-year period in a wet continental climate, utilizing stereo-photogrammetry to measure erosion. It reported an average erosion depth of 2 mm (0.5% of wall thickness) for walls stabilised with 5% hydraulic lime and 6.4 mm (1.6% of wall thickness) for unstabilised walls. The international literature often notes wood's susceptibility to decay and termite damage, especially in warm, humid climates. However, advancements in treatment methods such as thermal modification and the use of preservatives have significantly improved wood's durability, making it a viable material for long-lasting construction. Studies from Finland [82] further support this, showing that properly treated wood can maintain durability comparable to more traditional materials like concrete or steel, especially in residential construction.

Regarding aesthetic appeal, the limited focus on this aspect in the selected studies underscores a gap in understanding the visual and sensory aspects of sustainable building materials. While Mi, Chen [83] offer insights into the fabrication and characterisation of transparent wood for smart building applications, more research is needed to explore the aesthetic potential of other sustainable materials. Future studies could investigate sustainable materials' design possibilities and aesthetic qualities and their integration into architectural and interior design practices to enhance visual appeal while maintaining environmental integrity.

Energy efficiency emerges as a key theme in the discussion of sustainable construction materials, with several studies highlighting the potential of materials like straw bales and Cement Stabilized Rammed Earth (CSRE) to contribute to energy conservation in buildings. Despite the comprehensive exploration of energy performance in the selected studies, future research could delve deeper into optimising energy efficiency through material selection, design strategies, and technological innovations. Additionally, there is a need for more rigorous assessments of energy performance under real-world conditions and long-term monitoring to validate the effectiveness of sustainable materials in reducing energy consumption and carbon emissions.

Environmental impact considerations are central to discussions on sustainable construction materials, yet only a few studies directly address this aspect in the selected literature. However, these findings of Høibø, Hansen [80] underscore the complex interplay between durability perceptions, environmental attitudes, knowledge levels, and past experiences in shaping consumer preferences for building materials in urban housing contexts. While insights from Høibø, Hansen [80] and Alcorn and Donn [73] shed light on material preferences and CO_2 emissions reduction strategies, there is a notable gap in understanding the holistic environmental impact of sustainable materials throughout their lifecycle. Future research should adopt a lifecycle assessment approach to quantify environmental impacts, including resource extraction, manufacturing, transportation, use, and end-of-life disposal, to inform more sustainable material choices and construction practices.

Energy efficiency is a critical factor driving the adoption of construction materials such as strawbale, wood, and rammed earth due to their sustainability benefits. Strawbales offer excellent thermal properties comparable to high-insulation materials, making them suitable for reducing energy consumption and CO2 emissions in building projects. Rammed earth, particularly when stabilised with cement, exhibits lower embodied energy than traditional materials like burnt clay bricks, contributing to improved thermal comfort and reduced energy demands. Wood-based construction materials also demonstrate promise with lower embodied energy and CO_2 emissions than concrete or steel systems, enhancing their appeal in residential buildings.

Recent studies underscore the thermal and energy performance advantages of strawbale, wood, and rammed earth in sustainable construction practices. Studies highlight the ability of straw bales to maintain thermal stability and reduce heat loss, meet regulatory standards for air permeability, and demonstrate insulation and fire resistance. Rammed earth, known for reducing indoor temperature fluctuations and energy consumption, shows significant potential when stabilised with cement. Wood-based materials exhibit lower environmental impacts and superior thermal performance than conventional building materials, supporting their use in energy-efficient residential construction. The challenges and benefits of using straw bale construction are highlighted, noting issues with summer overheating but showcasing efficient energy consumption and sustainability through innovative building techniques. Research explores the dynamic thermal behaviour of straw walls in different building prototypes, revealing thermal conductance variations and construction methods' impact on energy performance.

These findings collectively underline the potential of strawbale, wood, and rammed earth as environmentally friendly building materials that can significantly contribute to energy-efficient and sustainable building designs. Future research could focus on refining construction techniques, optimising material properties, and addressing thermal performance challenges to further enhance these materials' viability and widespread adoption in global construction practices.

Energy efficiency drives the selection of sustainable construction materials like strawbale, wood, and rammed earth. These materials offer significant environmental benefits, such as reduced energy consumption and CO_2 emissions. Strawbales provide excellent thermal properties comparable to high-insulation materials, while rammed earth, particularly when stabilised with cement, exhibits lower embodied energy than traditional materials like burnt clay bricks. Wood-based construction materials show promise with lower environmental impacts and superior thermal performance compared to concrete or steel systems, supporting their use in energy-efficient residential buildings.

Two notable studies focus on the environmental impact of construction materials. One study highlights urban dwellers' preferences for non-wood materials in structural applications in Oslo, particularly among younger individuals favouring wood for cladding. The importance of assessing wood facades for environmental impact in urban housing development is emphasised, reflecting the growing interest in environmentally friendly building materials. Another study underscores the environmental benefits of using strawbale insulation and timber framing. It concludes that these materials can significantly reduce CO_2 emissions through carbon sequestration properties, contributing to sustainable construction practices. These findings underscore the growing recognition of environmental considerations in material selection, urging the building industry to prioritise sustainable alternatives for future urban housing development.

6 Conclusion

The primary aim of this study was to identify the best zero-carbon building materials in the construction industry. We focus on wood, rammed earth, and strawbales, evaluating them based on six key criteria: sustainability, cost-effectiveness, durability, aesthetic appeal, energy efficiency, and environmental impact. By examining these materials through these diverse lenses, our research aims to offer valuable insights for choosing the most suitable eco-friendly building components. Mostly, the term 'sustainability' is defined by thermal behaviour, energy performance, and life cycle assessment by the eligible articles we found. Therefore, we consider this in the field of energy efficiency. Key findings include:

- Durability Insights: The selected studies provide valuable insights into the durability of these materials, emphasizing the influence of environmental conditions on unsterilised rammed earth walls and the decay resistance of straw bales. While rammed earth walls can last over 20 years, future research is needed to standardise durability assessment methodologies and explore synergistic effects between different materials.
- Energy Efficiency: Energy efficiency is a prominent theme, with straw bales and CSRE demonstrating significant potential for reducing energy consumption and CO_2 emissions. Straw bales offer excellent thermal properties, while CSRE contributes to improved thermal comfort. The findings underscore the importance of rigorous assessments under real-world conditions to validate energy performance.
- Economic Considerations: Notably, there is a gap in research addressing the cost-effectiveness of these materials. While existing studies provide insights into the economic implications of material choices, further exploration is necessary to conduct comprehensive cost–benefit analyses that encompass both material costs and long-term maintenance expenses.
- Environmental Impact: Although the literature acknowledges the environmental benefits of using sustainable materials, there is a need for more in-depth lifecycle assessments to fully understand their impacts throughout production, use, and disposal. Future studies should adopt a lifecycle perspective to inform better material choices in sustainable construction.
- Aesthetic Appeal: The limited focus on the aesthetic aspects of sustainable materials presents a gap in understanding their visual and sensory qualities. Future research should investigate the integration of aesthetics in sustainable building practices to enhance their acceptance and appeal in architectural design.

Collectively, these findings affirm the potential of wood, rammed earth, and straw bales as environmentally friendly building materials that significantly contribute to energy-efficient and sustainable construction practices. Continued research is essential to refine construction techniques, optimise material properties, and address challenges related to durability and cost-effectiveness, ultimately supporting the wider adoption of these sustainable materials in the construction industry.

6.1 Future gaps and directions

Moving forward, several avenues for future research and development in sustainable construction materials emerge from the gaps identified in the existing literature. The studies reviewed highlight significant advances in understanding the durability and performance of various sustainable construction materials under different environmental conditions. However, several critical gaps remain that warrant further investigation:

1. Long-Term In-Situ Performance Evaluations: Future studies should focus on long-term assessments of these materials' performance across diverse climatic zones, especially under extreme weather events. This aligns with our findings that the durability of materials like unstabilised rammed earth is influenced by environmental factors, necessitating real-world data to validate their performance.
2. Cost-Effectiveness Analysis: The reviewed studies indicate a lack of research on the cost-effectiveness of using sustainable materials in the construction sector. Our findings stress the need to investigate not only the initial material costs but also the long-term operational and maintenance costs associated with materials such as wood, rammed earth, and straw bales. We recommend developing a comprehensive framework to assess cost-effectiveness by considering multiple factors, including:
   - Initial Material Costs: Including production, transportation, and installation costs.
   - Operational and Maintenance Costs: Analyzing long-term energy savings, maintenance needs, and repair/replacement costs throughout the building's life cycle.
   - Cost-Benefit Analysis: Conducting in-depth comparisons between traditional and sustainable materials to account for energy savings, environmental benefits (e.g., CO2 reduction), and any government incentives for green building.
3. Aesthetic Appeal: The aesthetic appeal of sustainable materials should also be investigated, as our review indicated limited focus on this aspect. Understanding how these materials can be effectively integrated into design practices is essential for broader acceptance in the market.
4. Case Studies and Field Experiments: Future research should include conducting case studies and field experiments to gather real-world data on the economic performance of these materials under various climatic and market conditions. This will provide a more holistic understanding of how materials perform not only environmentally but also economically over the long term.

Author contribution Conceptualization: Ali Hashemi Araghi; Methodology: Ali Hashemi Araghi; Formal analysis and investigation: Ali Hashemi Araghi; Writing—original draft preparation: Ali Hashemi Araghi; Writing—review and editing: Ali Hashemi Araghi, Eziaku Onyeizu Rasheed, V. Vishnupriya, Jeff Seadon; Resources: Ali Hashemi Araghi; Supervision: Eziaku Onyeizu Rasheed, V. Vishnupriya, Jeff Seadon.

Funding No funds, grants, or other support was received for conducting this study.

Data availability No datasets were generated or analysed during the current study.

Code availability No code was used in this study.

Declarations

Conflict of interest The authors declare no competing interests.

Appendix A: Summary of the findings from the selected studies

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[79]	Straw Bale	Thermal performance	515 mm thick walls	Two houses	Experimental measurement	The main results or findings regarding the thermal performance of straw bale walls include good insulating performance and high thermal inertia, the ability to offer energy savings and be used in green buildings, low cost, eco-sustainability, and potential for local economic development	N/A
[61]	Straw Bale	Durability and Indoor Comfort, Sound Insulation, and Energy Performance	N\A	Wall (A pilot sample building)	Laboratory evaluation	The results demonstrated that the Life Cycle Assessment demonstrates that the use of straw bales in walls can reduce the energy and carbon embodied in the building. The results also showed that the tested façade had quite poor performance compared with a traditional heavyweight or lightweight wall	Yearly thermal energy and electricity consumption per 1 m^2 of the wall in the winter season were measured by 8.19 and 2.34 kWh/m2/year, respectively. In conclusion, the study showed that straw bales have the potential for profitable use in the building sector, but several problems were also identified: the influence of moisture on the durability of the straw, the fire hazard during construction, the limited dynamic thermal performance and sound insulation
[73]	strawbale and timber	CO_2 emissions, Life Cycle Analysis, conventional insulation, and energy performance	N\A	The whole house (Eighteen 200m^2 houses)	Experimental measurement	The results showed that the building with strawbale, timber frame, and concrete floor, (41.7 GJ and 2.197 kg) compared to the standard house with code insulation, timber frame, and concrete floor (37.9 GJ and 1.903 kg) could drop the annual energy and annual Co_2-e by about 9% GJ and 13% kg, respectively	Also, they compared strawbale, timber frame, concrete floor and strawbale, timber frame, and suspended timber floor (36.9 GJ and 1.707 kg). The findings revealed that a building with suspended timber floors could reduce the annual energy and CO_2 by about 2.5% GJ for energy and 10% kg for CO_2. The total annual CO2-e reductions for strawbale insulation were 491 kg and 29%

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[64]	Wood	CO_2 emissions	N\A	Whole house (Two single-storey portal-frame buildings)	A comparative study	An analysis of typical forms of building construction shows that wood buildings require much lower process energy and result in lower carbon emissions than buildings of other materials such as brick, aluminium, steel and concrete	The study reveals that a 17% increase in wood usage in New Zealand's building industry could cut carbon emissions by 20%, equivalent to about 1.5% of the nation's total emissions. This reduction mainly results from substituting wood for materials like brick, aluminium, steel, and concrete, which require more energy. Consequently, there would be a corresponding 1.5% decrease in total national fossil fuel consumption. These findings have significant implications for global forestry and construction, highlighting the need for increased forest management for sustained wood production
[84]	Straw and wool	Insulation: Thermal resistance Vapour resistance	N\A	Wall (Three prefabricated wall panel)	The calculations have been manually conducted	The findings indicated that the thermal resistance and Vapour resistance of Panel 1 (straw) were about 7.2 m^2K/W and 4.714 MNs/g, which means straw could reduce these amounts by about 17%. However, the vapour resistance was slightly different, nearly 1%, compared to Panel 2	Panel 2 combines wool's low density and superior insulative properties with straw's ability to support the bio-based vapour-permeable material of clay plaster. Panels 1 and 2 seek to improve upon existing prefabricated straw panels by increasing the thermal resistance and decreasing the weight of the panel by incorporating pure wool insulation
[66]	Rammed earth	Durability	450 mm thick wall	Wall	Field measurement	The results showed that the estimated lifespan of the freestanding unstabilized rammed earth wall with minimal protection from natural climatic conditions in a temperate climate is between 37 and 75 years	N/A

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[85]	Wood, earth and straw	Thermal performance	550 mm thick wall	Modular wall, using a prefabricated system	Experimental tests	The thermal resistance of the wood, rammed earth, and straw bale are 0.17, 0.17, and 0.061 W/mK, respectively	Local earth from the site can be used for one- or two-level house buildings
[36]	Earth and Straw	Durability	N\A	N\A	Review analysis	In areas that experience up to 635 mm (25 in.) of rain per year, unstabilized earthen walls left unprotected are likely to erode at a rate of 25.4 mm (1 in.) in 20 years on vertical surfaces and 50–75 mm (2–3 in.) per year on horizontal surfaces	N/A
[83]	Transparent Wood	Aesthetics and thermal conductivity	60 mm × 60 mm × 2 mm	Wood block	Experiment	The results showed that aesthetic wood exhibits a thermal conductivity of 0.24 W m^{-1} K^{-1} in the radial direction, which is a lower thermal conductivity than that in the axial direction	The aesthetic wood with perpendicular lumina possesses a high transparency of ~ 80% with excellent UV-blocking properties and a high optical haze of ~ 93%, which leads to good anti-glare performance and light guiding to create a comfortable space contrasting with glass. It also had a low thermal conductivity
[80]	Wood compared with other materials	Durability and Environmental Impact	N\A	Using wood materials indoors	Questionnaire	The findings indicate that consumers in the Oslo area often prefer materials other than wood for various housing features	N\A
[63]	Stabilised and unstabilised rammed earth	Durability	About 50 cm thickness in general	Walls	Stereo-photogrammetry	The stabilised wall with 5% hydraulic lime showed no significant changes in quality after 20 years, with minor vertical cracks at the edges. Unstabilised, showed erosion, especially on the top two-thirds of the wall portion	Unstabilised with fine soil, it exhibited multiple cracks due to shrinkage, but only on the surface. Upper parts of walls are less eroded due to roof protection, and variation in density across compacted layers influences erosion

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[77]	Cement-stabilised rammed earth (CSRE)	Energy Consumption	155mm 600mm 700mm	Wallette	Experimental Analysis	It was found that CSRE walls with 8% cement showed a 17% higher compressive strength compared to brick masonry, and increasing the cement content to 12% resulted in a 60% increase in CSRE strength	The study compared the embodied energy in CSRE walls with 8% cement content to that of burnt clay brick masonry walls. It was found that the embodied energy in CSRE walls with 8% cement was only about 15–25% of the embodied energy in burnt clay brick masonry walls
[65]	Wood-based and concrete-based	Energy Performance	N/A	Wall	CORRIM assessment: Life Cycle Inventories	The corresponding energy benefit associated with wood-based building materials is approximately 132PJyear^{-1}. These estimates represent about 22% of embodied energy and 27% of embodied greenhouse gas emissions in the residential sector of the US economy over 100 years	Transitioning to wood-based construction could lead to substantial energy savings, with estimated reductions of 95PJ/year (wood vs. concrete) and 170PJ/year (wood vs. steel), averaging 132PJ/year. These figures represent approximately 10–34% (averaging 22%) of the 0.5–1.0EJ/year of embodied total energy associated with the US residential sector
[81]	Straw bale, wood, and bamboo	Carbon emissions and economic performance (cost)	N/A	A Net-zero energy building (Wall)	Simulation: EnergyPlus (DesignBuilder)	Biomass materials, which occupy most of the building structure, accounted for 36.01% of the total carbon emissions. Biomass materials have a better carbon footprint than non-biomass materials. For individual materials, the straw bale, wood bits, bamboo, and other wood products accounted for 2.85%, 1.15%, 0.15%, and 31.87%, respectively	The total was ¥490686 ($71114) and ¥3556 ($515) per square meter. The cost of labour was not considered in the calculations. The cost of biomass material accounted for 36.39% of the total cost. The straw bale, wood bits, bamboo, and other wood products accounted for 2.65%, 0%, 0.87%, and 96.48%, respectively. Therefore, wood and wood products accounted for the vast majority of the cost of all biomass materials. Non-biomass materials accounted for most construction costs

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[69]	Straw bale	Durability (humidity level)	Total thickness of 35 mm	Walls	Exposure test (Experimental)	The findings show that the three-year-old straw did not support any significant new microbial growth. However, a rapid increase in CO_2 concentrations was observed for the fresh straw, indicating rapid microbial growth	During the experimental period, the hygro-thermal conditions exceeded levels where degradation of the straw is understood to occur. This suggests that the conditions may have supported significant mould growth, which can impact the durability of the straw panel
[62]	Straw bale	Durability (moisture content and pH) and thermal stability	Total thickness of 50 cm	Wall	Laboratory measurements	The study found that relative humidity in the straw bales initially increased steeply, reaching 76.4% after 450 h, compared to the surrounding humidity of about 78%. The difference between surrounding and internal humidity decreased from 3.44% at 400 h to 2.55% by the end of the 450-h test	Average temperatures within the wall ranged from 12.7°C to 13.7°C initially. After 24 h, temperatures increased towards the wall interior, with differences of 0.04°C to 2.11°C compared to outside temperature. After 96 h, temperature percentages between ambient and wall interior varied (11.25% to 29.7%). Temperatures inside the straw were higher than outside plaster, showing superior insulation
[76]	Earth-straw	Thermal Performance	20-cm-thick	adobe walls	Experiment	Adobe exhibited a thermal transmittance 2.5 times higher than lightened boards, with board 2 showing the lowest thermal transmittance among the boards. Board 2 showed the highest temperature differences between both sides due to its insulating capacity, reaching the initial core temperature of 20°C first	Boards with long length (12 cm) showed higher thermal transmittance than those with short length (1–5 cm), possibly due to differences in panel density caused by the incorporation of slip during execution. Adobe exhibited a thermal transmittance 2.5 times higher than lightened boards, with board 2 showing the lowest thermal transmittance among the boards

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[74]	Straw bale	Sound insulation and thermal performance	3.6 m wide by 2.7 m high	Panel	Experiment	In the first test, emitting 100 dB of 'white noise' to the house's exterior resulted in a sound level drop, Rw value of 44 dB. In a subsequent test, emitting the same sound level to the house's exterior resulted in a sound level drop, Rw value of 48 dB. These values indicate that the prototype house had good sound insulation performance	The thermal survey on the prototype house revealed areas of conductive heat loss, thermal bridging, and building defects. Thermal images identified heat loss around doors and air infiltration around windows and door frames. Specific areas for improvement include refining internal ply strips, panel junctions, and internal corners of timber frames
[67]	Rammed earth	Durability and energy performance	1000 × 160 × 650 mm	Wall Panels	Experiment	The durability problems identified in cement-stabilized rammed earth (CSRE) construction are related to shrinkage cracks, thermal cracks, and erosion. The erosion rate of CSRE specimens with different cement contents shows that erosion rate reduces with higher stabilizer content	The embodied energy of cement-stabilized rammed earth (CSRE) walls was studied in comparison to burnt clay brick masonry. The study found that the embodied energy of CSRE is lower, ranging from 15–25% of burnt clay brick masonry. The contribution to operational energy is also discussed, indicating that rammed earth construction can lead to lower energy demand for thermal comfort, with about a 3°C reduction in indoor temperature compared to cement block wall

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[75]	Rammed earth	Thermal comfort and energy performance	N/A	A two-storey building	Questionnaire (subjective), field measurement, and simulation (TRNSYS)	The building did not adequately achieve thermal comfort during occupied hours. Operative temperatures in two out of the three offices measured were outside the comfort zone for over 20% of the time in the summer evaluation period. In the winter, the situation was worse, with the two top-floor offices providing thermal comfort only 70% of the time and the ground-floor office only 13% of the time	The building had a larger energy intensity than the target specified by the Australian Building Codes Board. The low electricity use did result in low greenhouse gas intensity. The installed solar system did not perform as intended. Computer modelling suggested that increasing the R-value of external walls through external insulation could improve energy efficiency. Unwanted air exchange, infiltration rates, and inadequate night purging affected thermal comfort and energy performance
[72]	Wood-based construction panels	Moisture (mould growth)-Durability	N/A	Sample boards	Experiment	Construction materials, especially wood-based panels, can be vulnerable to moisture-related problems and mould growth, which can lead to "Sick Building Syndrome" and poor indoor air quality. Simulated laboratory conditions revealed that construction plates were already contaminated with mould spores before arrival at the construction site, indicating the potential for mould growth on untreated surfaces	Wood-based construction plates made from materials like pinewood, oriented strand board, and waterproof birch plywood showed better resistance to mould growth compared to environmentally friendly wood-based panels

Sources	Studied material(s)	Research themes	Proportional of the material(s)	Building's elements/types	Methods	Summary of findings	Other consideration
[71]	Softwood-engineered wood products such as cross-laminated timber and laminated veneer lumber	Wood decay-Durability	900 × 45 × 90 mm	Wood panels	Experiment	Laminated veneer lumber samples showed minimal mycelium spread and localized damage compared to severe decay in untreated solid wood	Laminated veneer lumber demonstrated better resistance to decay compared to cross-laminated timber. Definitions and ratings for mould growth on wood samples, ranging from no perceivable mould to severe mould covering more than 50% of the surface (ratings from 1 to 5)
[70]	Engineering wood (oriented strand board)	Mold growth and wood decay	12 mm thickness	Exterior walls	Mathematical model (Hygrothermal models and damage functions)	The study indicates that mold growth increases with higher air leakage rates and decreases as the wall dries	The results suggest that the wood-rotting model shows the wall would start rotting from the bottom upward, emphasizing the significance of maintaining wood below the fibre saturation point for construction integrity
[78]	Straw bale	Thermal behaviour and energy performance	800 mm thickness	A building	Thermal-dynamic simulation	Straw bale buildings exhibit low heat capacity, making them prone to quick overheating in summer. Adding a clay wall coating can reduce heating demand but has minimal effect on overheating. The study highlighted the importance of managing solar gains and using external blinds to improve comfort in the building	The ECO46 straw bale building demonstrated efficient energy consumption compared to standard buildings. Utilizing solar panels, double-flow ventilation, and insulation contributed to the sustainability and energy efficiency of the building. The study concluded that straw bale buildings can be a sustainable alternative in the construction industry due to their low embodied energy and excellent thermal performance

*Thickness × width × height.

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