



LIFE CYCLE ASSESSMENT OF CONSTRUCTION MATERIALS: A REVIEW OF ENVIRONMENTAL PERFORMANCE AND FUTURE DIRECTIONS

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Abstract

The increasing demand for sustainable and resource-efficient buildings has intensified the need for comprehensive environmental assessment tools in the construction sector. Construction materials play a crucial role in determining the environmental performance of buildings throughout their life cycle, influencing energy consumption, resource depletion, waste generation, and greenhouse gas emissions. As the construction industry seeks to reduce its environmental footprint and support sustainable development goals, Life Cycle Assessment (LCA) has emerged as a widely accepted methodology for evaluating environmental impacts and supporting informed decision-making. This review paper examines the application of Life Cycle Assessment (LCA) to the evaluation of construction materials, with a particular focus on their environmental performance and recent developments in sustainable construction. The study reviews the life cycle impacts of commonly used materials, including concrete, steel, timber, aluminium, glass, and other structural and non-structural materials. The findings demonstrate that no construction material is environmentally superior in all situations and emphasize the importance of context-specific material selection based on comprehensive life cycle assessment. Integrating environmental, technical, and functional considerations through LCA can support more sustainable decision-making and contribute to the development of low-carbon, resource-efficient buildings and infrastructure.

Key words: *Life Cycle Assessment, Construction materials, Sustainability, Environmental impact*

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1. INTRODUCTION

The building sector contributes significantly to resource consumption, energy use, and greenhouse gas emissions, all of which have an adverse effect on the environment. Approximately 34% of energy-related CO₂ emissions and more than 32% of energy demand in 2023 came from the buildings and construction industry, making it a crucial sector for reaching global net zero carbon and resilience goals [1]. Rapid urbanization, infrastructure expansion, and population growth intensify pressure on natural resources and ecosystems [2]. Consequently, the transition toward sustainable construction practices has become a strategic priority at global, national, and industry levels. Construction materials have a significant impact on CO₂ emissions because their production often requires large amounts of energy [3]. Materials such as cement, steel, and concrete are among the largest sources of carbon emissions in the construction industry. Choosing sustainable, recycled, or low-carbon materials can greatly reduce the environmental impact of buildings. Therefore, the selection of construction materials plays a key role in reducing greenhouse gas emissions and supporting sustainable development.

Sustainability in construction refers to designing, building, and operating structures in a way that reduces environmental impact while promoting economic and social benefits. It involves using energy-efficient technologies, sustainable materials, and renewable energy sources. Sustainable construction helps conserve natural resources, reduce waste and carbon emissions, and create healthier living and working environments. As a result, it plays an important role in achieving long-term environmental and economic goals. Traditional approaches to environmental evaluation in construction focused primarily on operational energy consumption. However, growing evidence highlights the importance of embodied impacts associated with material extraction, production, transportation, construction, maintenance, and end-of-life processes. These embodied impacts can represent a substantial share of total life cycle emissions, particularly in energy-efficient buildings.

Life Cycle Assessment (LCA) provides a systematic framework for evaluating environmental impacts throughout the entire life cycle of a product or system [4]. In the context of construction materials, LCA enables quantitative comparison of alternative materials and supports evidence-based decision-making. This paper reviews methodological foundations, applications, limitations, and future directions of LCA in construction material assessment. It offers a comprehensive and methodical way to evaluate a material's environmental performance and find areas for improvement. Impacts including carbon emissions, energy use, water use, air pollution, waste production, and ecosystem depletion are measured by life cycle assessment (LCA) studies [5, 6]. In the construction industry, LCA is widely applied to assess the sustainability of building materials and construction systems by considering all stages, from raw material extraction and manufacturing to transportation, use, maintenance, and end-of-life treatment [4]. The concept of LCA is based on life cycle thinking, which recognizes that environmental impacts occur at every stage of a product's existence [7]. Rather than focusing only on the production phase, LCA evaluates the complete chain



of activities and material flows. It also considers the potential benefits of reuse, recycling, and resource recovery, emphasizing the circular nature of modern sustainable construction practices. LCA follows several fundamental principles that ensure consistency and reliability of the assessment. These include considering the entire life cycle of the system, defining clear system boundaries, maintaining transparency in data collection and methodological choices, evaluating all relevant environmental impacts, and applying consistent assessment procedures. By following these principles, LCA enables objective comparisons between alternative materials and construction solutions while supporting sustainability-oriented decision-making.

2. METHODOLOGY

This review was conducted to provide a comprehensive overview of the environmental performance of construction materials through the application of Life Cycle Assessment (LCA). A structured literature search was performed to identify relevant scientific publications addressing the environmental impacts of construction materials, LCA methodologies, embodied carbon, circular economy strategies, and emerging trends in sustainable construction. The literature search was carried out using four major scientific databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. The review primarily considered peer-reviewed journal articles published in English between 2006 and 2025, with particular emphasis on recent publications reflecting current advances in LCA methodology and sustainable construction.

The selection process focused on studies that (i) applied Life Cycle Assessment to construction materials or buildings, (ii) evaluated environmental impacts using recognized LCA methodologies, (iii) investigated embodied carbon, energy consumption, resource efficiency, or circular economy approaches, and (iv) presented findings relevant to sustainable material selection and environmental decision-making. Following the screening and evaluation process, references were selected for qualitative synthesis. The selected literature was analyzed comparatively to identify the environmental characteristics, advantages, limitations, and sustainability potential of major construction materials, as well as current research trends and future directions in Life Cycle Assessment within the construction sector.

3. ENVIRONMENTAL IMPACTS OF MAJOR CONSTRUCTION MATERIALS

Construction materials play a crucial role in determining the overall environmental performance of buildings. According to the Global Status Report for Buildings and Construction 2024–2025, buildings consumed 32% of global energy and contributed 34% of global CO₂ emissions in 2023 [8]. Emissions associated with building operations accounted for around 26% of total global emissions, primarily due to heating, cooling, lighting, and other energy-related activities. In addition, the production of construction materials such as cement, steel, and aluminium contributed approximately 5% of global emissions, while materials such as glass and bricks accounted for a further 3% [9]. Operational emissions from buildings reached nearly 9.8 gigatonnes of CO₂ in 2023,

highlighting the continued dependence of the sector on energy-intensive processes [10]. Although embodied carbon emissions related to construction materials decreased slightly to approximately 2.9 gigatonnes of CO₂, the overall reduction remains insufficient to meet global climate targets [11]. The main environmental characteristics of the most commonly used construction materials are summarized in Table 1.

Table 1. Environmental characteristics of major construction materials

Material	Main Advantages	Main Limitations	Environmental Characteristics	References
Cement	Excellent mechanical performance	High clinker-related CO ₂ emissions	Highest contribution to embodied carbon	[12], [13], [14], [15]
Concrete	High durability; thermal mass	Cement production dominates impacts	Environmental performance improves using SCMs and recycled aggregates	[6], [16], [17], [18]
Steel	High strength; fully recyclable	Energy-intensive primary production	High embodied energy but excellent recyclability	[15], [18], [19], [20]
Brick	Long service life	Energy-intensive firing	Moderate environmental impacts over long service life	[21], [22]
Timber	Renewable resource; carbon storage	Moisture sensitivity and durability issues	Lowest embodied carbon among structural materials	[18], [22]
Glass	High daylight utilization	High melting temperatures	High manufacturing energy demand	[20], [22]
Aluminium	Lightweight; corrosion resistant	Very high electricity demand during primary production	Recycling significantly reduces impacts	[23], [24]
Recycled construction materials	Resource conservation; waste reduction	Variable quality	Lower embodied carbon than virgin materials	[23], [24], [25], [26]

Concrete is the most widely used construction material in the world due to its durability, versatility, and relatively low cost [12]. However, its environmental impact is considerable, primarily because of cement production. The manufacturing of cement requires high-temperature kilns and releases large amounts of carbon dioxide (CO₂) both from fuel combustion and from the chemical process of limestone calcination. As a result, cement production is one of the largest industrial sources of global CO₂ emissions [13]. In addition to greenhouse gas emissions, concrete production consumes significant quantities of natural resources such as limestone, sand, gravel, and water. Nevertheless, concrete offers advantages such as long service life, thermal mass benefits, and the potential incorporation of recycled aggregates and supplementary cementitious materials that can reduce its environmental footprint [14, 15].

Steel is another fundamental construction material widely used in structural systems due to its high strength, durability, and flexibility. The production of steel is energy-intensive and generates substantial greenhouse gas emissions, particularly when manufactured using traditional blast furnace technology. Environmental impacts also include the extraction of iron ore and coal, resource depletion, and air pollution [15]. Despite these challenges, steel has one of the highest recycling rates among construction materials. Recycled steel requires significantly less energy than primary steel production, making circular economy strategies particularly effective in reducing its environmental impact.



Timber is often regarded as one of the most environmentally friendly construction materials because it is renewable and capable of storing carbon throughout its service life. Timber production generally requires less energy compared to concrete and steel manufacturing. However, the sustainability of timber depends on responsible forest management practices. Unsustainable logging can contribute to deforestation, biodiversity loss, and ecosystem degradation. Certified wood products sourced from sustainably managed forests offer significant environmental advantages and are increasingly promoted in green building projects. In a study of a residential building in Scotland, Asif et al. assessed the embodied CO₂ emissions of several commonly used construction materials [16]. The results indicated that concrete was the dominant contributor to embodied energy, accounting for 61% of the total, while ceramic tiles and timber contributed 15% and 14%, respectively [15]. These findings highlight the significant environmental impact of concrete compared with other building materials [15, 17].

Bricks and masonry products are widely used for walls and façades due to their durability, thermal performance, and fire resistance. Their production typically involves the extraction of clay and high-temperature firing processes, which consume considerable amounts of energy and generate CO₂ emissions. Although brick manufacturing can have notable environmental impacts, masonry structures often have long service lives and low maintenance requirements, which can partially offset their initial environmental burden over the building life cycle. In this context, alternative bricks are manufactured using either organic (ABO) or inorganic (ABI) additives, which are typically derived from industrial waste streams. A key distinction in their production process is the elimination of the firing stage, although this approach is not applicable to all types of alternative bricks [18]. According to Galan-Marín et al. (2016), the evaluation of alternative brick types should include comparisons not only with traditional brick (TB) but also with other construction systems, such as precast concrete, wood, bamboo, and similar materials [19].

Glass is an essential material in modern architecture, providing natural lighting, transparency, and aesthetic value. However, glass manufacturing requires high temperatures and substantial energy consumption, resulting in greenhouse gas emissions. Large glazed surfaces can also increase operational energy demand if not properly designed. On the other hand, advanced glazing technologies, such as low-emissivity (Low-E) coatings and double or triple glazing systems, can significantly improve building energy efficiency and reduce operational environmental impacts [20].

Aluminium is valued in construction for its lightweight properties, corrosion resistance, and durability. Nevertheless, primary aluminium production is highly energy-intensive and associated with significant greenhouse gas emissions. The extraction and processing of bauxite ore also contribute to environmental degradation. Despite these impacts, aluminium can be recycled repeatedly without substantial loss of quality, and recycled aluminium requires only a fraction of the energy needed for primary production, making recycling a key strategy for improving sustainability. One special quality of aluminium is that it can be recycled endlessly without losing its qualities. In comparison to the first mining and processing, recycling aluminium only



consumes 5% of the energy and 10% of the initial capital equipment expenditures [21]. Melting or casting and solid-state recycling are the two main processes used to recycle aluminium [22].

4. OVERVIEW OF LIFE CYCLE ASSESSMENT RESEARCH ON CONSTRUCTION MATERIALS

Life Cycle Assessment (LCA) provides a scientific basis for comparing the environmental performance of different construction materials and building systems. The comparison of LCA results is typically based on a range of environmental indicators, including greenhouse gas (GHG) emissions, energy consumption, water use, resource depletion, waste generation, human health impacts, and ecosystem effects. Since no single material performs best in every category, LCA helps identify trade-offs between different environmental objectives and supports balanced decision-making.

Studies consistently show that concrete and steel generally have higher embodied carbon emissions than timber-based materials [23, 24]. Cement production is a major contributor to the environmental impact of concrete, while steel manufacturing requires substantial energy and generates significant greenhouse gas emissions [25, 26]. In contrast, timber products often exhibit lower embodied energy and carbon footprints due to their renewable nature and carbon storage capacity [27, 28]. For example, timber structures can significantly reduce life-cycle carbon emissions compared to equivalent concrete or steel structures [29]. However, timber may require additional considerations regarding durability, fire resistance, and sustainable forest management practices. Therefore, environmental advantages should always be evaluated alongside technical and functional requirements. Aluminium often exhibits one of the highest embodied energy values among construction materials because of the energy-intensive extraction and refining processes involved in primary production. Nevertheless, its environmental performance improves substantially when recycled aluminium is used [21, 22]. Similarly, glass production can be energy-intensive, but high-performance glazing systems can reduce operational energy consumption throughout a building's service life, compensating for part of the initial environmental burden.

LCA comparisons frequently distinguish between embodied impacts and operational impacts. Embodied impacts include emissions and resource consumption associated with material extraction, manufacturing, transportation, construction, maintenance, and disposal. Operational impacts result from energy and water consumption during the use phase of a building [30, 31]. Traditionally, operational energy dominated the environmental footprint of buildings. However, improvements in energy-efficient building design have reduced operational impacts, making embodied carbon increasingly important. Consequently, material selection now plays a more significant role in the overall sustainability performance of buildings.

Comparative LCA studies reveal several consistent trends [30, 31]. Timber generally exhibits the lowest embodied carbon footprint among major structural materials, whereas concrete is associated with relatively high CO₂ emissions because of cement



production [32]. Steel is characterized by high embodied energy and greenhouse gas emissions but offers significant environmental advantages due to its high recyclability [33]. Primary aluminium production has one of the highest embodied energy requirements among construction materials; however, recycling substantially reduces its environmental impacts [34]. In general, recycled and secondary materials demonstrate lower environmental impacts than virgin materials across most impact categories [35].

5. FUTURE DIRECTIONS OF LCA IN CONSTRUCTION

Life Cycle Assessment (LCA) is continuously evolving in response to new sustainability goals, technological progress, and increasing environmental awareness in the construction industry. Future developments are strongly linked to circular economy principles, digital tools, standardized environmental data, and the use of low-carbon materials [36]. One of the most important future directions is the integration of LCA with circular economy strategies. Instead of the traditional linear model (take–make–dispose), the circular approach focuses on reducing waste, reusing materials, and recycling resources. LCA helps evaluate the environmental benefits of circular practices such as material reuse, component recovery, and recycling loops. By quantifying environmental savings, LCA supports the design of buildings that minimize resource depletion and extend material life cycles [37]. The use of digital technologies, especially Building Information Modelling (BIM), is transforming how LCA is applied in construction [38, 39]. BIM enables the integration of material quantities, building design data, and environmental databases in a single digital environment. When combined with LCA software, BIM allows for real-time environmental impact assessment during the design phase [39]. This integration improves decision-making, reduces errors, and enables designers to optimize buildings for lower environmental impact before construction begins. Environmental Product Declarations (EPDs) are becoming increasingly important as standardized and transparent sources of environmental data for construction materials [39]. EPDs provide verified information on the life cycle environmental impacts of products, based on LCA methodology. The growing availability of EPDs improves data quality in LCA studies and supports more reliable and comparable environmental assessments in the construction sector.

Several European countries, including Germany, France, and the Netherlands, have promoted the use of low-carbon cement, recycled steel, and sustainably sourced timber, which has contributed to lower embodied carbon emissions within the construction sector [40]. These materials help reduce greenhouse gas emissions while maintaining the required structural and functional performance of buildings [41]. Similar initiatives have emerged in North America. In the United States, the Federal-State Buy Clean Initiative encourages the procurement of lower-carbon construction materials for publicly funded projects [42]. Participating states prioritize environmentally responsible material selection, supporting market demand for products with reduced life-cycle emissions. Such policies demonstrate the growing role



of sustainable procurement strategies in accelerating the transition toward a low-carbon built environment.

6. CONCLUSION

Construction materials differ significantly in their environmental performance throughout their life cycle, making material selection a key aspect of sustainable construction. The reviewed literature shows that no single material is environmentally superior in all situations. Timber generally exhibits the lowest embodied carbon footprint, while concrete and steel are associated with higher greenhouse gas emissions due to cement production and energy-intensive manufacturing. Although aluminium and glass require considerable energy during primary production, their environmental performance can be significantly improved through recycling and efficient use. Life Cycle Assessment (LCA) remains the most comprehensive tool for evaluating the environmental impacts of construction materials by considering their entire life cycle. Future developments, including the integration of circular economy principles, Building Information Modeling (BIM), Environmental Product Declarations (EPDs), and digital technologies, are expected to improve the reliability and practical application of LCA. Overall, sustainable construction requires context-specific material selection based on comprehensive life cycle assessment that considers environmental, technical, and functional performance to support the transition toward a low-carbon and resource-efficient built environment.

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