Ingeniería y Competitividad
Vol 27 (3) 2025 doi: 10.25100/iyc.v27i3.15244

Vol 27 (3)

ISSN
0123-3033
e- 2027-8284

Original Article

Reducing the carbon footprint in materials and industrialized building construction

Reducción de la huella de carbono en materiales y construcción de edificios industrializados

Jesús D. Márquez Montejo[1] Romel J. Gallardo Amaya[1]

[1]Universidad Francisco de Paula Santander Ocaña, Grupo de Investigación GIGMA, Ocaña, Colombia.

How to cite?

Márquez JD, Gallardo RJ. Reducing the carbon footprint in materials and industrialized building construction. Ingeniería y Competitividad, 2025, 27(3) e-20815244.

https://doi.org/10.25100/iyc.v27i3.15244

Received: 16/09/25
Reviewed: 24/10/25
Accepted: 6/11/25
Online: 9/12/25

Correspondence

jdmarquezm@ufpso.edu.co

Abstract

Introduction. The growth of construction and the adoption of industrialized systems increase the consumption of materials and the carbon embodied in the material (A1-A3), transport (A4), and construction (A5) modules of a life cycle assessment (LCA). This article identifies trends and parameters, quantifies the 100-year global warming potential (GWP100) of A1–A5 in a representative building, and prioritizes mitigation strategies.
Objective. This research aims to establish carbon footprint reduction strategies by identifying trends and research parameters in an industrialized building archetype within the Colombian context.
Methodology. A bibliometric analysis is performed in Scopus to understand recent trends and influential parameters in reducing embodied carbon in industrialized buildings. Next, GWP100 is quantified in A1–A5 with the archetype, using One Click LCA (LCA: Life Cycle Assessment) software. Finally, mitigation strategies are identified and prioritized.
Results. The industrialized building reached 140.51 kg CO_2 e/m² in A1–A5. The improved scenario (cement with less clinker, recycled steel, optimized transportation, and equipment electrification) reduced the impact to 85.57 kg CO_2 e/m², a reduction of 39.10%. The most effective strategies were associated with the selection of sustainable materials.
Conclusions. Early specification decisions, such as cements with higher clinker substitution, 100% scrap steel, and verifiable Environmental Product Declarations (EPDs), together with the selection of short transport routes and equipment electrification, represent the strategies with the most significant impact reduction.

Keywords: Carbon footprint, Global warming, Sustainable development, Construction materials, Construction industry.

Resumen

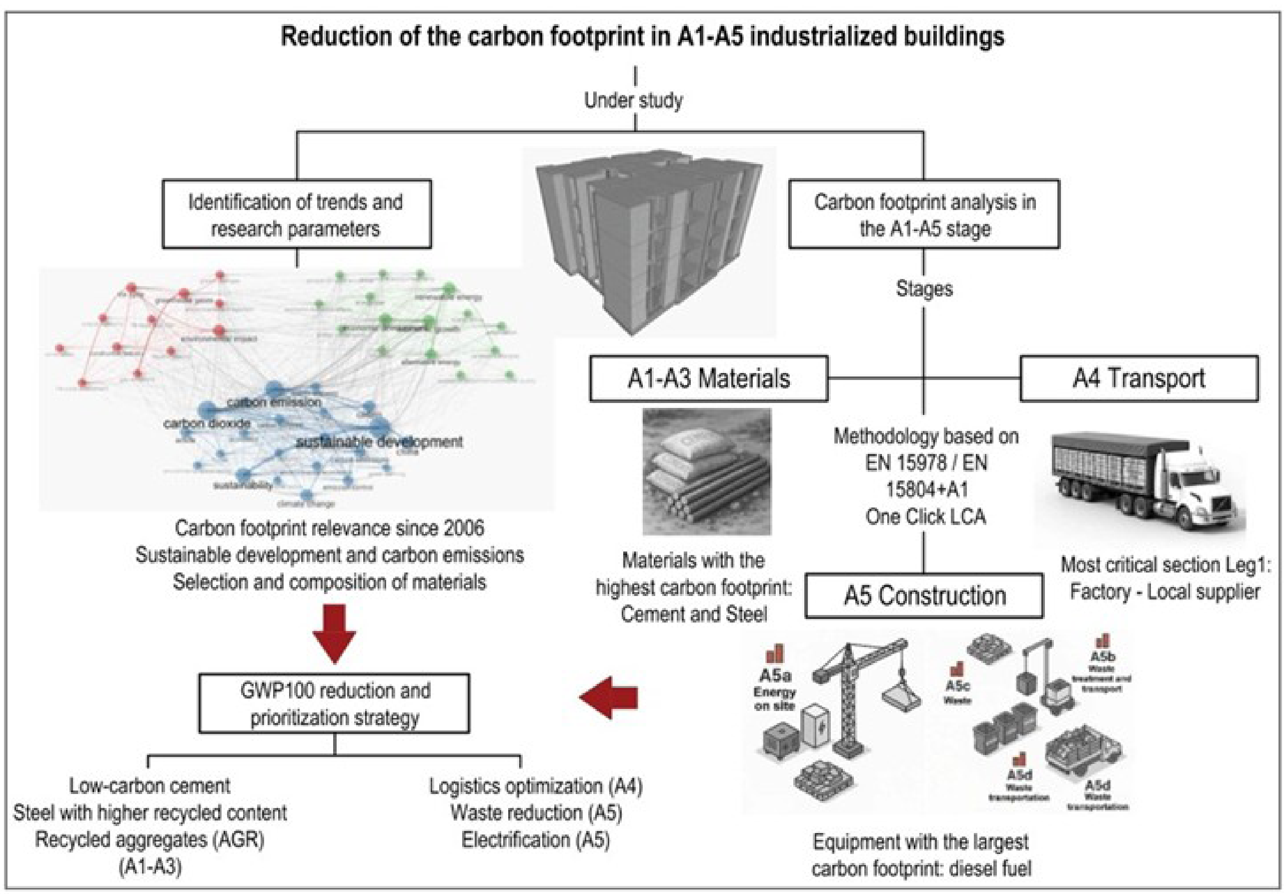
Introducción. El crecimiento de la edificación y la adopción de sistemas industrializados aumentan el consumo de materiales y el carbono incorporado en los módulos de materiales (A1-A3), transporte (A4) y construcción (A5) de un análisis de ciclo de vida (ACV). Este artículo identifica tendencias y parámetros, cuantifica el potencial de calentamiento global a 100 años (GWP100) de A1–A5 en un edificio representativo y prioriza estrategias de mitigación.
Objetivo. El objetivo de esta investigación es establecer estrategias de reducción de la huella de carbono identificando tendencias y parámetros de investigación en un arquetipo de edificio industrializado dentro del contexto colombiano.
Metodología. Se realiza un análisis bibliométrico en Scopus para entender tendencias recientes y parámetros influyentes en la reducción del carbono incorporado en edificios industrializados. Luego, se cuantifica el GWP100 en A1–A5 con el arquetipo, usando el software One Click LCA (LCA: Life Cycle Assessment). Finalmente, se identifica y se prioriza las estrategias de mitigación.
Resultados. El edificio industrializado alcanzó 140,51 kg CO_2e/m² en A1–A5. El escenario mejorado (cemento con menor clinker, acero reciclado, transporte optimizado y electrificación de equipos) bajo el impacto a 85,57 kg CO_2 e/m², una reducción del 39,10 %. Las estrategias más efectivas se asociaron a la selección de materiales sostenibles.
Conclusiones. Las decisiones tempranas de especificación como cementos con mayor sustitución de clínker, acero 100% chatarra y declaraciones ambientales de producto (EPD: Environmental Product Declaration) verificables, junto con selección de rutas cortas de transporte y la electrificación de equipos, representan las estrategias con mejor reducción del impacto.

Palabras clave: Huella de carbono, Calentamiento global, Desarrollo sostenible, Materiales de construcción, Industria de la Construcción.

Why was this study conducted?
This study was conducted with the aim of establishing strategies to reduce the carbon footprint of industrialized buildings by analyzing a representative archetype of the Colombian context. The study identified important trends and parameters, while quantifying the GWP100 impact in the materials and construction stages (A1-A5), allowing mitigation strategies to be prioritized.

What were the most relevant findings?
The industrialized building had a total carbon footprint of 140.51 kg CO2e/m² built in stages A1-A5. Cement was the material with the highest contribution (72.64%), followed by reinforcing steel (19.22%). Transportation and on-site construction contributed less, but still had a significant impact. By implementing improvements such as partially replacing clinker with slag, using recycled steel, optimizing transportation, and electrifying equipment, the footprint was reduced by 39.10% to 85.57 kg CO2e/m².

What do these findings contribute?
These results highlight the importance of early decisions in the project to select materials with lower impacts, as well as optimizing logistics and construction processes to reduce the carbon footprint. The study confirms that the focus should be on the production stages (A1-A3), but without neglecting transport and construction (A4-A5). The methodology and proposed model offer a useful tool for guiding sustainable construction policies and practices in the Colombian context.



doi: 10.25100/iyc.v27i3.15244

Introduction

The construction sector is one of the most relevant industries worldwide and among the most polluting. It is estimated to contribute nearly 40% of global greenhouse gas (GHG) emissions (1) and which, according to the European Parliament, consumes around 36% of total energy. A considerable portion of these emissions is associated with the intensive extraction of raw materials and the transport and manufacturing processes, which require up to 2 tons per square meter of constructed area (2).

Concrete is the planet's most widely used construction material, and cement production accounts for between 5% and 8% of global CO_2 emissions (3). Approximately 1.6 billion tons of cement are consumed annually (4), and its production releases, on average, 0.56 tons of CO_2 per ton of cement (5). This makes the cement industry one of the most carbon-intensive, with impacts exceeding those of other manufacturing sectors, as indicated by the United Nations Environment Programme (UNEP).

Throughout their life cycle, buildings represent a significant share of global GHG emissions (6). Traditionally, most mitigation efforts have focused on reducing operational emissions (heating, cooling, lighting), historically accounting for nearly 75% of the total, according to a UNEP report. As operational emissions decrease due to efficiency improvements and grid decarbonization, the relative share of embodied carbon in the building life cycle increases and can equal or even surpass operational emissions in high-performance buildings (7). In parallel, several studies estimate that materials and construction already contribute about 11% of the total building sector emissions at a global scale (8).

CO_2 emissions in buildings are divided into two categories: embodied (design, production, and construction) and operational (use) (9). While the latter shows a downward trend, the former requires greater attention due to the lag in mitigation strategies (6). In particular, materials such as cement, steel, and aluminum account for most embodied carbon (3).

The main structural materials used in high-rise buildings are reinforced concrete and structural steel. More than 99% of tall building structures are currently constructed with these two materials (10). Since they concentrate most of the embodied carbon, adopting industrialized or modular construction approaches has emerged as a mitigation pathway, with reported average reductions of 15–20% compared to traditional methods (11).

Life Cycle Assessment (LCA) has become a key tool for evaluating environmental impacts in buildings, particularly when applied under recognized standards such as EN 15978, which defines the assessment modules from production to the use and end-of-life phases. In this regard, Al-Obaidy et al. (12) demonstrated through a parametric study using the One Click LCA software that comparing different construction systems (concrete, steel, and hybrid) allows for identifying substantial differences in global warming potential and other impact indicators. Their work confirms the usefulness of EN 15978 in standardizing assessments and supporting decision-making toward lower-impact construction solutions.

doi: 10.25100/iyc.v27i3.15244

In the life cycle analysis of buildings, the initial product stage (A1–A3)—including raw material extraction (A1), transport to the plant (A2), and manufacturing processes (A3)—represents the main source of embodied carbon emissions, accounting for over 70% of the total in most cases (13,14). Module A4, related to transporting materials to the construction site, shows a secondary contribution, although it is sensitive to travel distance, vehicle type, and logistics efficiency (15). Meanwhile, Module A5, which includes assembly activities, on-site energy consumption, and waste generation, can reach significant impact levels in contexts of low construction efficiency or limited waste control, underscoring the need to optimize both the supply chain and installation processes (16,17).

In Colombia, the construction sector represents a significant source of environmental impact due to its high consumption of natural resources and generation of greenhouse gas emissions. According to the Colombian Green Building Council (CCCS), buildings account for around 7% of the country's total GHG emissions, which may rise to between 12% and 16% when the agricultural and forestry sectors are excluded. According to Rivera García, in his research on embodied carbon, recent studies have shown that the embodied carbon in social housing buildings (VIS and VIP) in Bogotá ranges between 158 and 231 kg CO_2eq/m^2, with the product (A1–A3) and construction (A4–A5) stages being the most significant contributors, accounting for 81.6% and 9.6% respectively. In this context, the international standards ISO 14040 and ISO 14044 establish the principles and methodological framework for Life Cycle Assessment (LCA). This recognized tool comprehensively evaluates material, energy, and emission flows throughout a building's life cycle.

Consequently, this study aims to determine strategies for reducing embodied carbon in the A1–A5 stages of industrialized buildings by quantifying the footprint through a representative model using the One Click LCA software and comparing material and process scenarios within the Colombian context.

Methodology

The research design can be classified as mixed with a descriptive approach, since it includes a qualitative component for identifying the parameters and strategies associated with reducing the carbon footprint in industrialized buildings. Subsequently, a quantitative component is incorporated to evaluate the carbon footprint using Environmental Product Declarations (EPD) and the One Click LCA software in a representative industrialized building (see Figure 1), to identify critical points for the proposed strategies. The following section describes the phases carried out for the development of the research:

doi: 10.25100/iyc.v27i3.15244

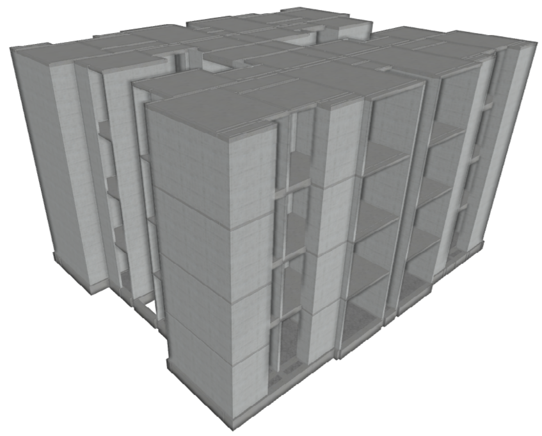


Figure 1. BIM digital representation of the industrialized building (own elaboration)

Phase 1. Identification of Trends and Parameters

This bibliometric study performs a systematic analysis of the international scientific production on the carbon footprint of industrialized buildings, using records from the Scopus database. To complement this global analysis, a national-level literature review was also conducted to identify the main research trends and the specific parameters that influence carbon footprint reduction in industrialized buildings in Colombia.

Phase 2. Carbon Footprint Analysis in Stages A1–A5

The embodied carbon in the A1–A5 stages of industrialized buildings is quantified through a representative model developed using the One Click LCA software, which complies with the international standards ISO 14040 and ISO 14044 — the methodological foundations of Life Cycle Assessment (LCA). Likewise, the tool is fully aligned with European standards EN 15978 and EN 15804, which regulate the environmental assessment of buildings and Environmental Product Declarations (EPD), ensuring consistency with the international frameworks applicable to the construction sector.

Initially, the material quantities of the building—focused on the structural and foundation systems (concrete and reinforcing steel)—are calculated in order to determine the carbon footprint impact using different EPDs (A1–A3). In addition, assumptions are made for transport (A4) and construction processes (A5) to assess the construction impact of the baseline case study: a representative archetype of an industrialized residential building, hereafter referred to as the initial scenario or Model 1.

doi: 10.25100/iyc.v27i3.15244

Phase 3. Reduction and Prioritization Strategies

Based on the trend, parameter analysis, and the representative model, strategies for reducing the carbon footprint in the material (A1–A3) and construction (A4–A5) stages of industrialized buildings are identified and prioritized. The factors influencing carbon footprint reduction are first determined and ranked; then, decision-making schemes are developed, and strategies are defined to propose an improved alternative — hereafter referred to as the *enhanced*, *alternative scenario*, or *Model 2*.

Results

The results are presented according to the three methodological phases. First, the bibliometric and literature review synthesizes key trends and parameters; then, the representative model estimates the GWP100 in stages A1–A5 of the life cycle analysis; finally, reduction strategies are evaluated and prioritized according to their effect.

Identification of Trends and Parameters

For the bibliometric analysis, the most effective search was obtained using the following keywords: *Industrialized building* and *Carbon Footprint*, which yielded 1,786 related documents. After processing the data exported from Scopus in BibTeX format, the information was analyzed in RStudio using the *Bibliometrix* package. A filtering process was applied, resulting in 1,765 documents. These records were further refined to remove duplicates and ensure that metadata were complete, guaranteeing the quality of the results and traceability.

Bibliographic Production

Figure 2 shows that industrialized buildings and carbon footprint were scarcely published before 2006, with fewer than three documents per year. From that year onward, research and publications on the subject increased significantly, highlighting its growing relevance and reaching 364 papers indexed in Scopus by 2024.

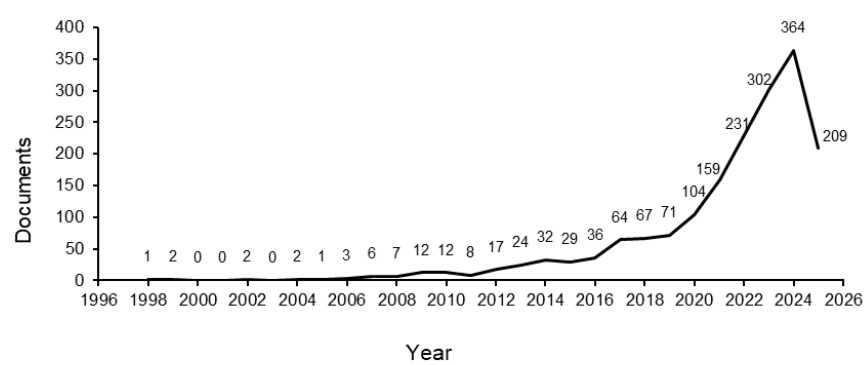


Figure 2. Annual scientific production related to carbon footprint and industrialized buildings between 1996 and 2025 (author's elaboration)

doi: 10.25100/iyc.v27i3.15244

Keyword Co-occurrence Network

The keyword co-occurrence network shown below reveals three well-defined thematic clusters or groups of interconnected nodes (see Figure 3):

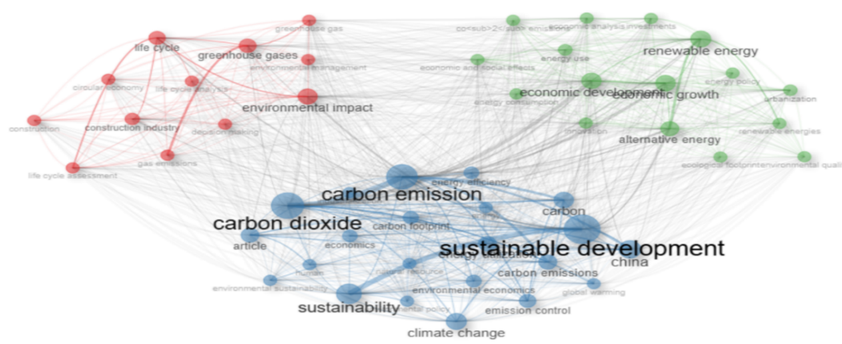


Figure 3. Keyword co-occurrence network (author's elaboration using Biblioshiny/Bibliometrix)

Blue Cluster (center–bottom): Groups the most frequent terms — sustainable development, carbon emission, carbon dioxide, and sustainability. Its size and central position indicate that emission mitigation and sustainable development constitute the backbone of the field, serving as a bridge connecting nearly all other concepts.

Red Cluster (left): Concentrates terms such as life cycle, construction industry, circular economy, and life cycle assessment, indicating studies focused on assessing the environmental impact of buildings throughout their entire life cycle and introducing circular economy strategies in construction processes.

Green Cluster (upper–right): Integrates renewable energy, alternative energy, economic development, and economic growth. This cluster is dominated by research linking energy transition with economic expansion and urbanization policies.

Research Trends

Thematic Focus. According to the analyzed clusters, the main focus of research revolves around sustainable development, carbon emissions, and climate change. Additionally, since 2023, technological approaches such as BIM and 3D printing have gained attention, and by 2025, greater emphasis is projected on modular construction and economic analysis.

The bibliometric analysis reveals that current research trends on the carbon footprint of industrialized buildings mainly address:

i. the incorporation of digital tools such as BIM to integrate life cycle analysis at early design stages;
ii. the adoption of industrialized and modular construction systems emphasizing material

doi: 10.25100/iyc.v27i3.15244

efficiency and emission reduction;

iii. the exploration of clinker substitution strategies, recycled steel use, and recycled aggregates; and

iv. the growing focus on circular economy models and policy evaluation for sectoral decarbonization.

These research lines represent the core of the current agenda and define the most extensively studied parameters in the specialized literature.

Research Parameters

The international bibliometric analysis identified research trends and the parameters that directly influence the reduction of carbon footprints in industrialized buildings. The most relevant parameters are summarized below:

Construction Materials

The selection and composition of construction materials stand out as one of the most determining factors in reducing the carbon footprint. Particularly noteworthy are: partial clinker replacement in cement production using SCMs (slag, pozzolans, LC^3, fly ash) and recycled steel and aggregates.

Industrialized Construction Processes

Construction processes play a decisive role in the overall environmental impact. The use of industrialized techniques and technologies has proven effective in reducing carbon emissions—especially prefabrication and modular construction—which exhibit lower CO_2 impacts than traditional building methods. Likewise, process optimization through integrating BIM and LCA tools is emphasized.

Energy and Emissions

Energy management is another key factor in reducing the carbon footprint of industrialized buildings. Strategies include transitioning to renewable energy sources during construction and operation, and reducing energy consumption through efficient design.

Structural Design and Optimization

Structural design decisions directly affect material consumption and, consequently, the carbon footprint. Parameters such as modularity, 3D printing to minimize waste, and section optimization for reduced material use are highlighted.

Economic and Policy Management

Finally, the economic and regulatory dimensions emerge as cross-cutting factors in implementing low-carbon strategies.

In Colombia, reducing the carbon footprint in the construction sector has become a national priority aligned with strategies such as the Colombian Low-Carbon Development Strategy (ECDBC), which promotes comprehensive decarbonization of the sector through energy efficiency, renewable energy use, and sustainable material and waste management.

doi: 10.25100/iyc.v27i3.15244

Several local academic studies have applied Life Cycle Assessment (LCA) to quantify and optimize buildings' carbon footprint, highlighting that locally supplied structural materials—mainly concrete and reinforcing steel—represent the majority of embodied emissions in industrialized constructions (18). Likewise, modular and industrialized construction has been recognized as a practical approach to reduce waste, accelerate processes, and minimize on-site environmental impacts.

Carbon Footprint Analysis in Stages A1–A5

A comprehensive reduction of a building's carbon footprint requires first addressing the embodied emissions generated before occupancy: raw material extraction, input manufacturing, and major construction activities (modules A1–A5 of standards EN 15804 or EN 15978). Therefore, this phase aimed to quantify the embodied carbon footprint of a representative industrialized building during its production and construction phases, using Environmental Product Declarations (EPD) as the primary data source and One Click LCA software as the modeling and calculation platform.

Defining the system boundary is essential for the industrialized building's carbon footprint analysis. NTC-ISO 14044 defines this as "a boundary based on a set of criteria specifying which unit processes are part of the system under study," ensuring that all processes analyzed across the different stages are consistent, transparent, and comparable. The system boundary proposed for the archetype is shown in Figure 4

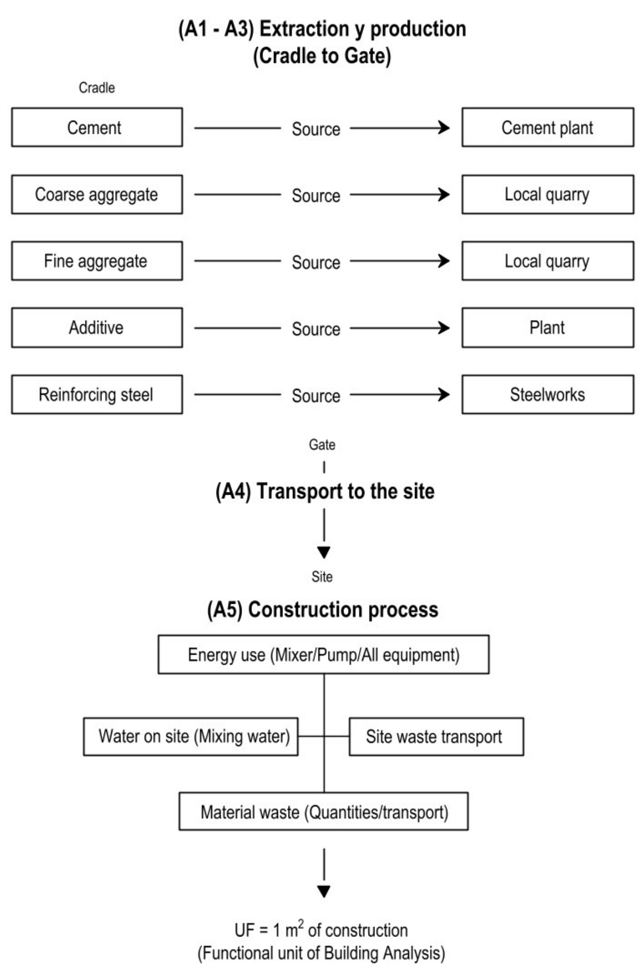


Figure 4. Diagram illustrating the system boundary for modules A1–A5 (own elaboration)

doi: 10.25100/iyc.v27i3.15244

The archetype corresponds to a mid-rise residential building (4 stories) with an industrialized construction system, featuring a total built area of 732.12 m² and an approximate floor area of 183.03 m² per level. The structure consists of shallow foundations using slabs and foundation beams, load-bearing reinforced concrete walls, and floors and roof systems composed of solid slabs with thicknesses ranging from 0.10 to 0.12 m.

The analysis focuses exclusively on the structural system —foundations and superstructure— made of reinforced concrete, since these elements account for 70% to 90% of the total embodied carbon in buildings of this type (6).

The study adopts a Colombian context, per the Colombian Earthquake-Resistant Construction Code (NSR-10), which establishes design requirements and material specifications for reinforced concrete and structural steel to ensure the strength and ductility of buildings in a country with high seismic activity. In stages A1–A3, the supply of locally produced cement with mineral additions and recycled steel is considered. At the same time, module A4 evaluates ground transportation from the plant to the construction site, representing the predominant logistics system in the sector.

According to data from the International Energy Agency (IEA), Colombian energy mix, used for the electrical processes of production and construction (A1–A5), has a high share of hydroelectric generation (75%), followed by natural gas (13%) and coal (8%), resulting in a low-carbon-intensity energy matrix (26). Finally, the analysis incorporates typical national supply chains and waste rates consistent with local construction practices and efficiency guidelines, accurately representing the conditions of an industrialized building in Colombia.

Construction Materials A1–A3

For the carbon footprint analysis in stages A1–A3 (production, transportation, and manufacturing of materials), it was necessary to determine the origin of the materials used to identify the most representative Environmental Product Declarations (EPDs) and the corresponding material quantities used in the building.

Table 1 presents the archetype data used to calculate the carbon footprint for module A1–A3. The archetype building was characterized by a total constructed area of 732.12 m².

Table 1. Quantities and type of resource for the calculation of kg CO_2 e/kg for module A1–A3

Materials	Quantity (kg)	Source (One Click LCA)	Impact kg CO_2e/kg
Cement	109.197,99	CEM III/A, 50% GGBS	0,65
Fine aggregate	224.468,34	Sand used in industries	0,0036
Coarse aggregate	190.684,19	Crushed rock, 8–16 mm	0,0043
Additive	1.638,55	Concrete admixture (EFCA)	1,31
Steel reinforcement	24.433,92	Reinforcement steel (rebar)	0,77

Source. Own elaboration

doi: 10.25100/iyc.v27i3.15244

Transport to the Construction Site (A4)

To calculate the environmental impact of transport to the construction site for module A4, the transportation routes were analyzed to determine the distances and types of transport used in each segment.

> According to One Click LCA, this module includes transporting products and packaging from the manufacturer's production plant to the construction site. It is necessary to identify the location of facilities and the mode of transport. Several scenarios may occur, mainly depending on whether a product is delivered to a specific destination or whether the transport impact varies according to the number of delivery locations based on sales data. If only one location is considered, the transport mode must be identified (alternatively, an average distance and transport type may be used), and the distance must be calculated. Reliable sources should be used to estimate distances depending on the mode of transport (ship, truck, etc.).

Table 2 presents the complete transport chain and the type of vehicle assigned to each route, defined according to the material transported and the distance covered for the archetype under the proposed conditions.

In the calculation of module A4 (material transport), only the outbound distance between the production site and the construction site was considered, since the transport profile used —Truck, double trailer, 30–34 ton, E5 (+A1), ref. year 2018, LKW-Zug— from the ÖKOBAUDAT database already includes the average empty return trips within its emission factors. This profile, developed per EN 15804 +A1, incorporates representative market-based return trips, thereby avoiding double counting of distances and loads.

Table 2. Transport detail for calculating module A4

Profile reference	Software / Source	Description	Distance (km)	Impact kgCO2e/tonkm
Truck-double trailer, 30-34 ton, E5	One Click LCA (OKOBAUDAT)	Cement transportation (leg1)	450	0,0644
		Steel transportation (leg1)	507	
		Formwork transportation (leg1)	234	
Truck, Small, 12 – 14 ton, E5	One Click LCA (OKOBAUDAT)	Coarse aggregate transportation (leg)	19,2	0,1289
		Fine aggregate transportation (leg)	19,2	
		Cement transportation (leg2)	4,5	
		Steel transportation (leg2)	4,5	
Truck, semi trailer, 20-26 ton, E5	One Click LCA (OKOBAUDAT)	Additive transportation (leg1)	601	0,0897
Delivery van, 7.5-12 ton, E5	One Click LCA (OKOBAUDAT)	Additive transportation (leg2)	4,5	0,2277

Source. Own elaboration

doi: 10.25100/iyc.v27i3.15244

Construction Process (Installation A5)

According to EN 15978, the impacts associated with on-site construction activities are reported under module A5 of the building-level Life Cycle Assessment (LCA). In accordance with this, One Click LCA divides module A5 into the following components: on-site energy use, on-site water use, material waste, and the management and transport of waste/packaging. Methodologically, the evaluation of buildings can also refer to ISO 21931-1, adopted in Colombia as NTC-ISO 21931-1:2022.

According to NTC-ISO 21930:2021, the information module "installation" comprises the execution of the construction product within any type of civil works and includes the following elements:

A5, waste of construction products, including the production processes (A1 to A3) and the transport to site (A4), to account for the material lost due to product waste;

A5, treatment of waste derived from product packaging and product losses, including the transport occurring during construction processes up to the system boundary, between product systems, or to final waste disposal;

A5, installation of the product at the construction site, including the manufacture and transport of auxiliary materials, as well as any direct energy use or freshwater consumption required for installation on site;

A5, preparation of the specific site for the installation of the declared product, including auxiliary materials and waste management, where applicable.

For the carbon footprint calculation, references for electrical and diesel-powered equipment were used, based on the resources listed in Table 3.

Table 3. Origin of the resource for calculating kg CO2e of the equipment

Equipment	Resource reference/ Source	Country/Year	Energy or Consumption	Impact kgCO2e/unid
Electrical Equipment	Electricity, Colombia, 2019 / One Click LCA	Colombia/2022	0,66 kWh/m^2	0,38 kg CO_2e/ kWh
Diesel Equipment	Diesel combusted in building machine / One Click LCA	World/2023	0,88 L/m^2	3,35 kg CO_2e/L

Source. Own elaboration

Carbon Footprint of the Archetype Building

After entering the material quantities and configuring the transport (A4) and construction (A5) assumptions —including energy use from electrical and fuel-powered equipment— the calculation was performed using One Click LCA software, which complies with EN 15978, employing EPDs in accordance with EN 15804 +A1.

doi: 10.25100/iyc.v27i3.15244

The tool provides results divided by modules A1–A5 and by impact categories. This study reported the GWP100 (Global Warming Potential over 100 years) expressed in kg CO_2e as the main indicator (see Table 4).

Table 4. Summary of results by category according to One Click LCA

	Results category	Global warming kg CO2e	Biogenic carbon storage kg CO2e bio	Ozone Depletion kg CFC11e	Acidification kg SO2e	Eutrophication kg PO4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ
A1-A3 (?)	Construction Product	93252,31	0	0	261,25	76,69	14,57	0,36	30327139,99
(-) A4 (?)	Transportation to Construction	6264,65	0	0	14,3	3,4	-4,71	0	83696,86
A4	Transportation to Construction Site	6185,45		0	14,12	3,36	-4,65	0	82639,42
A4-leg2	Transportation to Construction Site - Leg 2	79,19	0	0	0,18	0,04	-0,06	0	1057,44
(-) A5 (?)	Installation/Construction Process	3355,35		0	7,21	1,62	0,47	0,01	632055,19
A5a	Site Operations and Site Waste Management	2351,14		0	4,35	0,8	0,37	0	32463,36
A5b	Transportation of Site Waste	5,6		0	0,01	0	-0	0	74,71
A5c	Construction Site - Material Waste - Materials	937,97		0	2,71	0,78	0,15	0	598707,09
A5d	Construction Site - Material Waste - Transportation	60,64		0	0,14	0,03	-0,05	0	810,04
	Total	102872,31	0	0	282,76	81,72	10,33	0,36	31042892,04
	By gross interior area m2	140,51	0	0	0,39	0,11	0,01	0	42401,37

Source: Prepared by the authors based on results from One Click LCA

For the A1–A5 scope, the building's total GWP100 is 102,872.31 kg CO_2e (≈ 103 t CO_2e). When normalized by the functional unit, this corresponds to 140.51 kg CO_2e/m² of constructed area.

In Figure 5, the GWP100 values of the resources are shown, already considering the impacts from A1 to A5. It can be observed that the resource with the highest contribution to GWP100 is cement, accounting for 72.64%, followed by reinforcing steel with 19.22%. It is noteworthy that fuel consumption has a relatively low impact (2.02%), although still higher than the electricity consumption of on-site equipment (0.17%).

doi: 10.25100/iyc.v27i3.15244

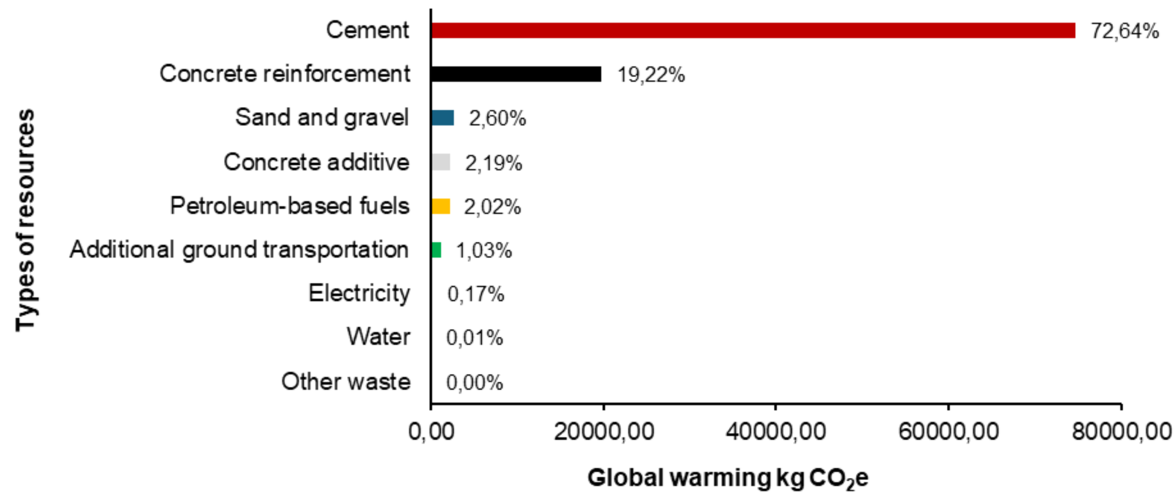


Figure 5. Global warming kg CO2e by resource type (own elaboration)

Regarding the structural system, Figure 6 reports the GWP100 of the structure divided by components. The values correspond to the sum of the evaluated impacts (A1–A5), excluding energy and fuel consumption from equipment, water use, waste management, and additional transport or travel activities. The kg CO_2e are mainly concentrated in the load-bearing frame (49.30%) and the upper slabs (28.40%), followed by the foundation (21.05%).

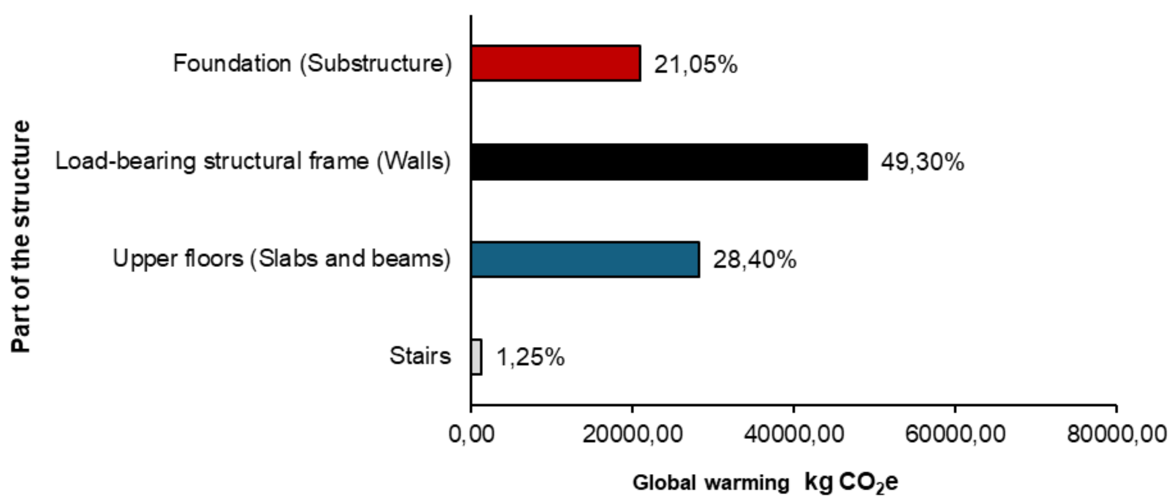


Figure 6. Global Warming Potential (kg CO_2e) by Structural Components (own elaboration)

In Figure 7, it is evident that the GWP100 impact is mainly concentrated in modules A1–A3 (material production). At the construction system level, the structural load-bearing frame and upper slabs account for the highest contribution, while in terms of material type, cement ranks first, followed by reinforcing steel.

doi: 10.25100/iyc.v27i3.15244

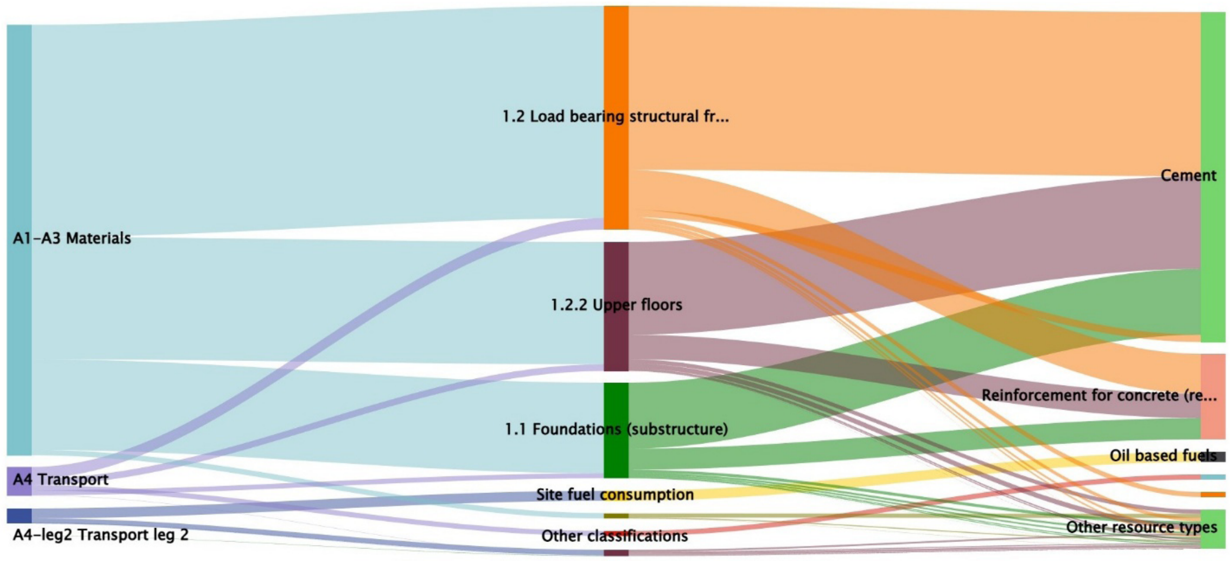


Figure 7. Sankey diagram (own creation using One Click LCA)

Scenario Comparison

When a scenario incorporating more sustainable materials, shorter transport distances, and electrification of on-site equipment was proposed, the carbon footprint of the archetype building was reduced. Table 5 presents the plan of changes implemented for the new scenario.

Table 5. Changes made with alternative materials (A1-A3) and strategy in A4 and A5

Step	Change Description	Resource reference	Impact Model 1	Impact Model 2
A1-A3	Blast furnace cement with 60% slag	CEM III/A, 60% GGBS	0,65 kg CO_2e/kg	0,40 kg CO_2e/kg
	Reinforcing steel: 100% scrap	Reinforcement steel scrap (Gerdau,Tultitlan plant)	0,77 kg CO_2e/kg	0,38 kg CO_2e/kg
A4	Cement supplier changed (205 km)	Truck, double trailer, 30-34 ton, E5	0,0644 kg CO_2e/tkm	0,0383 kg CO_2e/tkm
A5	Diesel pump changed to electric.	Electricity, Colombia, 2020, One Click LCA	3,35 kg CO_2e/L	0,38 kg CO_2e/kWh

Source. Own elaboration

When calculating the carbon footprint of the building under the new scenario (Model 2), an impact of 85.57 kg CO_2e/m^2 was obtained. Compared to the initial scenario (Model 1), this represents a 39.10% reduction in the carbon footprint across stages A1–A5 (see Figure 8).

doi: 10.25100/iyc.v27i3.15244

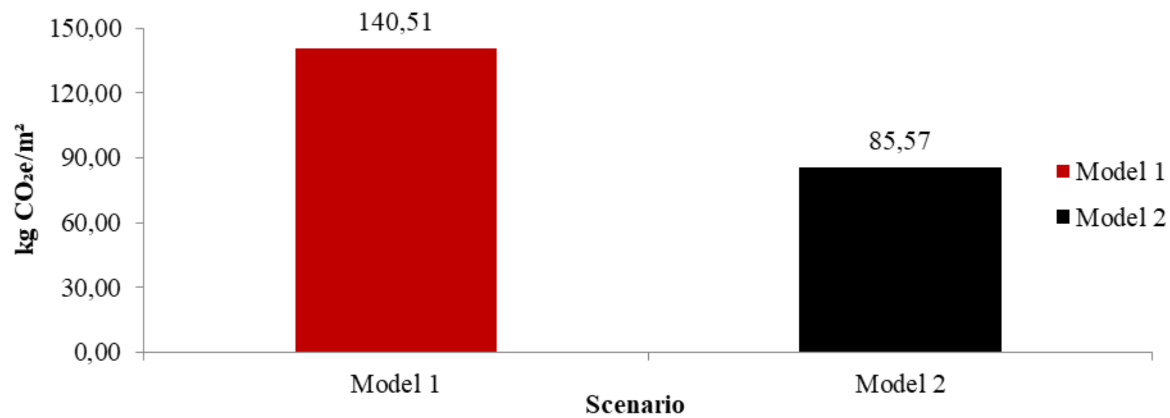


Figure 8. Comparison of carbon footprint reduction scenarios (Own elaboration)

Reduction and Prioritization Strategies

The proposed strategies focused on the stages of embodied carbon within the system boundary up to the construction site, including on-site operations (A1–A5). The general framework of the strategies is presented in Figure 9.

The strategies were prioritized based on the parameters with the greatest influence on the carbon footprint (GWP100) and on the performance of materials, transport, and installation processes for the archetype within stages A1–A5.

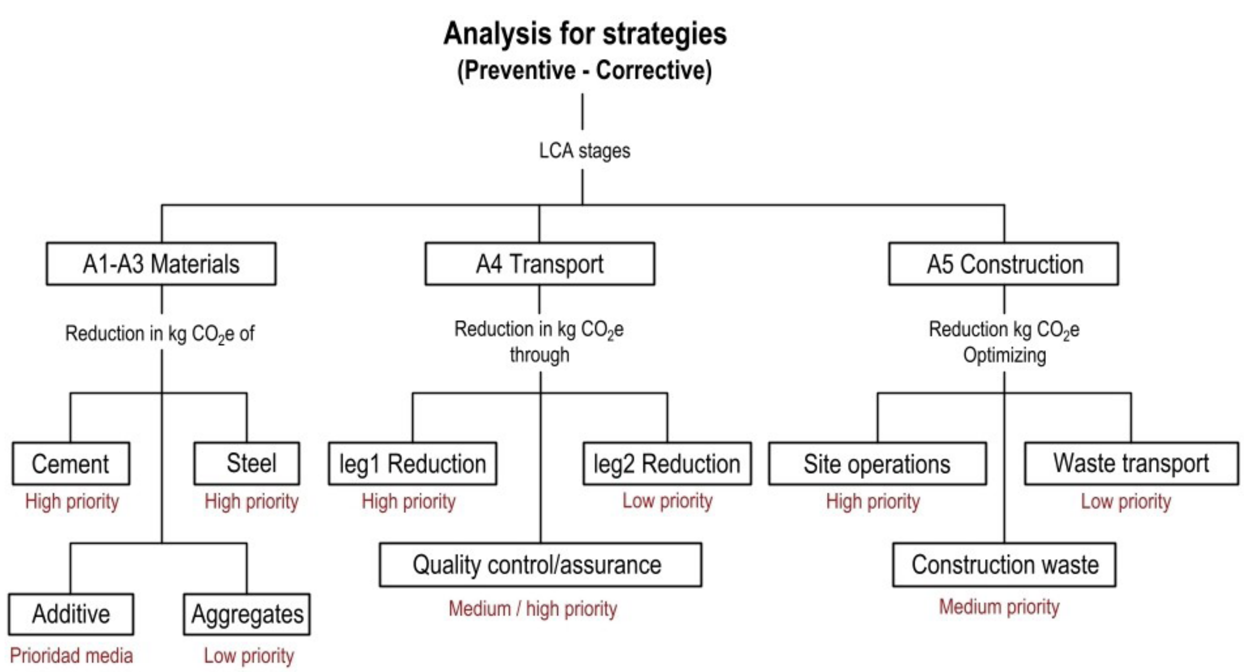


Figure 9. Guiding framework for the analysis of strategies (own elaboration)

doi: 10.25100/iyc.v27i3.15244

Strategies for Stages A1–A3 (Materials)

The proposed strategies were largely focused on the materials with the greatest contribution to the carbon footprint—namely cement and reinforcing steel—although additional measures were also considered for other materials.

To reduce the carbon footprint generated by cement, as identified throughout this study, it is essential to substitute clinker with supplementary cementitious materials (SCMs), such as slag, pozzolans, and others.

In cement production, alternative inputs can be used in specific proportions, which helps reduce the carbon footprint impact. Table 6 presents the weight percentages of each conventional input and its sustainable alternative, as reported by the Ministry of Environment and Sustainable Development of Colombia in its guide to sustainable building materials.

According to the guide to sustainable building materials, once cement is used to produce concrete, it cannot be recovered for recycling. However, waste or demolished concrete can be recycled during new cement manufacturing in controlled quantities, either as an alternative raw material for clinker production or as an additive by grinding clinker with gypsum and other aggregates.

Table 6. Comparisons of conventional and alternative cement inputs

Conventional inputs		**Alternative inputs**	
Stone aggregates	80%	Residual lime from acetylene production, construction and demolition waste	75%
Gypsum	10%	Pozzolanic materials: slag and ash (thermal waste), rice husk ash, construction and demolition waste	25%

Source: Adapted from the Ministry of Environment and Sustainable Development of Colombia

The use of low-GWP cements significantly reduces the kg CO_2e emissions in industrialized buildings, which have high concrete—and consequently, cement—consumption. Therefore, it is recommended to select suppliers with an Environmental Product Declaration (EPD) in accordance with EN 15804 / NTC-ISO 21930:2021, compare the results, and choose the option with the lowest carbon footprint.

In the case of steel, as shown in Table 7, following the recommendations of the guide to sustainable building materials, conventional inputs can be substituted or replaced by alternative materials, thereby reducing the environmental impacts generated throughout the material's life cycle.

Table 7. Comparisons of conventional and alternative inputs for steel

Conventional Inputs		**Alternative inputs**	
Coal	5%	Scrap	100%
Iron ore	95%		

Source: Adapted from the Colombian Ministry of Environment and Sustainable Development

doi: 10.25100/iyc.v27i3.15244

An effective strategy to reduce the carbon footprint is to partially replace the natural coarse aggregate with recycled coarse aggregate (RCA) from construction and demolition waste (CDW). For structural concrete, full replacement is not feasible: NTC 6421 allows a maximum substitution of 20% RCA for structural hydraulic concretes up to 35 MPa, provided that the material complies with NTC 174 and the component classification according to NTC 6422, as well as the provisions of Chapter C.5 of the Colombian Earthquake-Resistant Construction Code NSR-10.

Although the direct impact of admixtures in A1–A3 is low due to their small dosage, they are an important strategy since they enable cement reduction without compromising performance. It is advisable to select polycarboxylate ether (PCE) superplasticizers to lower the water/cement ratio (w/c) and achieve lower cement content per cubic meter while maintaining the same workability; verify compatibility with low-clinker and SCM (slag, pozzolans, LC3) cements to prevent unwanted setting delays or entrained air; and use admixtures with EPDs and supplier data indicating the lowest carbon footprint per declared unit.

Strategies for Stage A4 (Transport)

- The strategies focused on reducing transport distances, particularly leg 1, which accounts for the highest emissions due to the long distance between the supplier's plant and the construction site.
- Prioritize local or regional suppliers to minimize travel distances; schedule consolidated deliveries during off-peak hours and establish return logistics to reduce empty trips.
- Replace long-distance segments with rail or barge transport, maintaining truck transport only for the last leg.
- Require the use of EURO VI vehicles, biofuels, or electric vehicles in urban areas.

Strategies for Stage A5 (Construction)

- To define strategies for reducing the carbon footprint in A5, on-site operations were prioritized, as fuel and electricity consumption are the main contributors to this module's impact.
- Implement a site energy management plan to optimize equipment idle times.
- Where feasible, promote the electrification of cranes and small machinery or the use of biofuels.
- Adopt modular design and prefabrication to reduce cutting, ensure just-in-time material delivery, and protect stockpiles to minimize losses.
- Implement on-site segregation, establish packaging return agreements, and select nearby valorization facilities.
- Optimize waste logistics (routes, modes, and loads). Establish proper on-site procedures and planning to optimize waste movement—i.e., strategically locate waste storage areas.
- Select the nearest landfills for waste removal and transport.

doi: 10.25100/iyc.v27i3.15244

Discussion of Results

In Model 1, the material production phase (A1–A3) was the main determinant of the carbon footprint of the industrialized building archetype, accounting for 90.65% of the total impact. Cement represented 72.64% of emissions, while reinforcing steel contributed 19.22%.

The transport (A4) and construction (A5) modules represented 6.09% and 3.26%, respectively, of total emissions, indicating a smaller yet significant contribution. In A4, emissions were mainly attributed to long-distance transport by heavy trucks. In contrast, in A5, diesel consumption by machinery exceeded electricity use, confirming the importance of logistics optimization and the transition toward low-carbon construction processes.

Finally, the alternative scenario (Model 2) achieved a 39.1% reduction in the carbon footprint of the initial archetype building, validating the effectiveness of strategies such as partial clinker substitution with slag, using 100% recycled steel, transport optimization, and electrification of on-site equipment. These results highlight the need for local and up-to-date Environmental Product Declarations (EPDs). Although this study was based on a representative building, the applied methodology constitutes a useful tool for guiding design and construction decisions in the Colombian context.

Conclusions

The study of the carbon footprint in industrialized buildings is an emerging field that has evolved from being scarcely explored to rapidly expanding, gaining relevance since 2006 with an annual growth rate of approximately 21.9% up to 2024. Research lines focus on sustainable development, carbon emissions, and climate change, with Life Cycle Assessment (LCA), Building Information Modeling (BIM), and 3D printing as prominent topics.

To reduce the carbon footprint, the main parameters identified are the selection and composition of materials, particularly partial clinker substitution with Supplementary Cementitious Materials (SCMs), the use of recycled steel and aggregates, and, complementarily, the adoption of industrialized construction techniques such as prefabrication and modularity, as well as digital tools such as BIM implementation.

In assessing the carbon footprint of the archetype building, the selection of Environmental Product Declarations (EPDs) for each material proved crucial, since the impact factors and system boundaries defined by each EPD determine the unit impacts (e.g., kg CO_2e/kg) which, when multiplied by the modeled quantities, define the total footprint (kg CO_2e). This approach enables the identification of the life cycle stages (A1–A5) with the highest contribution and where reduction strategies should be prioritized.

When modeling a more sustainable scenario, by selecting materials with lower-impact EPDs according to sustainability criteria for an archetype, a 39.10% reduction (–54.94 kg CO_2e/m^2) was achieved compared to the initial model. The study confirms that the materials phase (A1–A3) concentrates the largest share of the carbon footprint and therefore must be prioritized in the LCA.

doi: 10.25100/iyc.v27i3.15244

The carbon footprint reduction strategies in industrialized buildings should be defined from the early design and planning stages through the selection of low-impact EPDs and logistics optimization. The results confirm that the greatest reduction potential lies in A1–A3, where cement is the largest contributor, followed by reinforcing steel. In summary, carbon footprint mitigation actions in industrialized buildings should focus primarily on A1–A3 through the selection of more sustainable EPDs, without overlooking A4–A5, where improvements are also attainable: switching from diesel to electric energy in on-site equipment reduces impacts in A5, and shortening the transport distance of cement by sourcing from a closer supplier has a positive effect on the A4 module.

CrediT authorship contribution statement

Conceptualization - Ideas: Jesús David Márquez Montejo. Formal analysis: Jesús David Márquez Montejo. Investigation: Jesús David Márquez Montejo. Methodology: Romel Jesús Gallardo Amaya. Project Management: Romel Jesús Gallardo Amaya. Resources: JJesús David Márquez Montejo. Validation: Jesús David Márquez Montejo. Writing - original draft - Preparation: Jesús David Márquez Montejo. Writing - revision and editing - Preparation: Romel Jesús Gallardo Amaya.

Conflict of interest

The authors declare that they have no conflicts of interest related to this research. Ethical aspect: does not declare.

References

1. Butters C, Cheshmehzangi A, Bakhshoodeh R. Sustainable Construction: The Embodied Carbon Impact of Infrastructures and Landscaping. Urban Science 2024, Vol 8, Page 76 [Internet]. 28 de junio de 2024 [citado 10 de septiembre de 2025];8(3):76. https://doi.org/10.3390/urbansci8030076

2. Bautista J, Loaiza N. Impactos de la construcción sostenible y tradicional a nivel ambiental. Boletín Semillas Ambientales. 2018;12.

3. Khaiyum MZ, Sarker S, Kabir G. Evaluation of Carbon Emission Factors in the Cement Industry: An Emerging Economy Context. Sustainability 2023, Vol 15, Page 15407 [Internet]. 29 de octubre de 2023 [citado 10 de septiembre de 2025];15(21):15407. https://doi.org/10.3390/su152115407

4. Shivaprasad KN, Yang HM, Singh JK. A path to carbon neutrality in construction: An overview of recent progress in recycled cement usage. Journal of CO2 Utilization [Internet]. 1 de mayo de 2024 [citado 10 de septiembre de 2025];83:102816. Disponible en: https://doi.org/10.1016/j.jcou.2024.102816

5. Cheng D, Reiner DM, Yang F, Cui C, Meng J, Shan Y, et al. Projecting future carbon emissions from cement production in developing countries. Nat Commun [Internet]. 1 de diciembre de 2023 [citado 10 de septiembre de 2025];14(1):1-12. Disponible en: https://doi.org/10.1038/s41467-023-43660-x

doi: 10.25100/iyc.v27i3.15244

6. Myint NN, Shafique M. Embodied carbon emissions of buildings: Taking a step towards net zero buildings. Case Studies in Construction Materials [Internet]. 1 de julio de 2024 [citado 10 de septiembre de 2025];20:e03024. Disponible en: https://doi.org/10.1016/j.cscm.2024.e03024

7. Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings - The hidden challenge for effective climate change mitigation. Appl Energy [Internet]. 15 de enero de 2020 [citado 10 de septiembre de 2025];258:114107. Disponible en: https://doi.org/10.1016/j.apenergy.2019.114107

8. Zhong X, Hu M, Deetman S, Steubing B, Lin HX, Hernandez GA, et al. Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. Nat Commun [Internet]. 1 de diciembre de 2021 [citado 10 de septiembre de 2025];12(1):1-10. Disponible en: https://doi.org/10.1038/s41467-021-26212-z

9. Sizirici B, Fseha Y, Cho CS, Yildiz I, Byon YJ. A review of carbon footprint reduction in construction industry, from design to operation. Materials [Internet]. 1 de octubre de 2021 [citado 10 de septiembre de 2025];14(20). Disponible en: https://doi.org/10.3390/ma14206094

10. Ma L, Azari R, Elnimeiri M. A Building Information Modeling-Based Life Cycle Assessment of the Embodied Carbon and Environmental Impacts of High-Rise Building Structures: A Case Study. Sustainability 2024, Vol 16, Page 569 [Internet]. 9 de enero de 2024 [citado 11 de septiembre de 2025];16(2):569. Disponible en: https://doi.org/10.3390/su16020569

11. Wei J, Ge B, Zhong Y, Lee TL, Zhang Y. Comparative analysis of embodied carbon in modular and conventional construction methods in Hong Kong. Sci Rep [Internet]. 1 de diciembre de 2024 [citado 11 de septiembre de 2025];14(1):1-20. Disponible en: https://doi.org/10.1038/s41598-024-73906-7

12. Al-Obaidy M, Courard L, Attia S. A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. Sustainability (Switzerland) [Internet]. 1 de marzo de 2022 [citado 11 de septiembre de 2025];14(6):3370. Disponible en: https://doi.org/10.3390/su14063370

13. Minunno R, O'grady T, Morrison GM, Gruner RL. Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. 2021 [citado 11 de septiembre de 2025]; Disponible en: https://doi.org/10.1016/j.rser.2021.110935

14. Huang Z, Zhou H, Miao Z, Tang H, Lin B, Zhuang W. Life-Cycle Carbon Emissions (LCCE) of Buildings: Implications, Calculations, and Reductions. Engineering [Internet]. 1 de abril de 2024 [citado 11 de septiembre de 2025];35:115-39. Disponible en: https://doi.org/10.1016/j.eng.2023.08.019

15. Kanafani K, Magnes J, Lindhard SM, Balouktsi M. Carbon Emissions during the Building Construction Phase: A Comprehensive Case Study of Construction Sites in Denmark. Sustainability 2023, Vol 15, Page 10992 [Internet]. 13 de julio de 2023 [citado 11 de septiembre de 2025];15(14):10992. Disponible en: https://doi.org/10.3390/su151410992

16. Wei J, Liu S, Guo H, Wang H, Wang J. Comparative analysis of embodied carbon in modular and conventional buildings. Buildings [Internet]. 2024;14(8):1866. Disponible en: https://doi.org/10.3390/buildings14081866

17. Amarasinghe I, Jayasinghe P, Alahakoon C. Paving the way for lowering embodied carbon emissions in the building and construction sector: A critical review. Clean Technol Environ Policy [Internet]. 2024;26:4359-77. Disponible en: https://doi.org/10.1007/s10098-024-03023-6

18. Análisis del ciclo de vida y emisiones de carbono en tres alternativas de sistemas constructivos para un proyecto de edificios para viviendas multifamiliares [Internet]. [citado 25 de octubre de 2025]. Disponible en: https://acofipapers.org/index.php/eiei/article/view/4598/2756

doi: 10.25100/iyc.v27i3.15244