

Article

Sustainable Material Selection in Colombian Construction: Integrating Structural Performance, Environmental Impact, and Regulatory Considerations

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Abstract

This study assesses the technical performance and environmental impact of traditional and eco-efficient materials used in civil construction in Colombia through a structured synthesis of scientific, technical, and regulatory evidence covering the period 2010–2025. The analysis integrates mechanical performance indicators, environmental footprint metrics, and the national regulatory framework supporting sustainable material adoption. Results show that conventional materials—Portland cement, structural steel, ceramic bricks, and timber—remain essential due to their proven structural reliability but are also responsible for the highest contributions to CO₂ emissions, energy consumption, and resource depletion. In contrast, eco-efficient alternatives, including blended concretes with mineral additions, geopolymers, rammed earth, *Guadua angustifolia*, and natural biocomposites, achieve carbon emission reductions between 40% and 85% while maintaining comparable mechanical performance for specific applications. Colombian policies—notably Resolutions 1257 of 2021 and 0194 of 2025—promote waste valorization and low-impact materials, yet their implementation remains limited by technical, economic, and knowledge barriers. The findings support a decision-oriented framework for material selection that balances structural efficiency with environmental responsibility.

Keywords: sustainable construction; eco-efficient materials; environmental impact assessment; carbon footprint; life cycle assessment (LCA); circular economy; construction and demolition waste; low-carbon materials



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1. Introduction

The construction sector plays a central role in economic and social development at both global and national levels, acting as a key driver of infrastructure growth, employment generation, and urban expansion. However, it is also one of the most resource-intensive industries worldwide and a major contributor to environmental degradation. The production and use of conventional construction materials—such as Portland cement, structural steel, ceramic bricks, and natural aggregates—are associated with high energy consumption, significant greenhouse gas emissions, and the generation of large volumes of solid waste.

These impacts have intensified concerns regarding the sustainability of current construction practices and have highlighted the urgent need for strategies that promote resource efficiency and environmental responsibility.

In Colombia, the construction industry represents a substantial share of the national Gross Domestic Product and is a major source of employment. Despite its economic importance, the sector faces critical environmental challenges, particularly related to the extraction of non-renewable natural resources and the management of construction and demolition waste. Rapid urbanization and increasing demand for housing and infrastructure have exacerbated these pressures, leading to higher material consumption and a growing environmental footprint. As a result, the transition toward more sustainable construction models has become a strategic priority within national environmental and development agendas.

The environmental burden of conventional construction materials is well documented. According to the International Energy Agency, the cement industry alone accounts for approximately 7% of global CO₂ emissions, largely due to energy-intensive clinker production and the calcination of limestone [1]. Colombia follows this global trend, as cement and concrete remain dominant materials in civil works and building construction. In addition, the extraction of aggregates and the disposal of construction and demolition waste contribute to ecosystem degradation, land use conflicts, and increased carbon emissions. These challenges underscore the need to rethink material selection and construction processes without compromising structural safety, durability, or performance.

In response to these concerns, growing attention has been directed toward the development and application of eco-efficient construction materials. These materials often incorporate industrial by-products or construction waste, including recycled aggregates, fly ash, blast furnace slag, powdered glass, and plastic residues, as partial or total substitutes for conventional raw materials [2,3]. Such alternatives align with circular economy principles by reducing the extraction of virgin resources, lowering embodied energy and carbon emissions, and promoting the reuse of waste within productive cycles. Recent studies suggest that, when properly designed and applied, eco-efficient materials can achieve mechanical and durability properties comparable to those of traditional materials while offering significant environmental advantages [4].

Despite their potential, the adoption of eco-efficient materials in the Colombian construction sector remains limited. Several barriers hinder their widespread implementation, including the lack of consolidated technical information, limited practical experience in real projects, and regulatory constraints that restrict their use in structural applications. Although policies such as Resolution 1257 of 2021 issued by the Ministry of Environment and Sustainable Development promote the integral management of construction and demolition waste, important technical and regulatory gaps persist [5]. Furthermore, existing technical standards and guidelines, including those developed by ICONTEC, have not yet fully incorporated sustainability criteria that enable the systematic use of alternative materials without compromising structural safety and quality [6].

From a research perspective, the available literature reveals that many studies focus either on the environmental benefits of eco-efficient materials or on their mechanical performance in isolation. However, relatively few works provide integrated, comparative analyses that simultaneously evaluate technical performance, environmental impact, and regulatory applicability within a specific national context. This lack of comprehensive, decision-oriented assessments generates uncertainty among engineers, designers, contractors, and policymakers, limiting confidence in the use of alternative materials for civil infrastructure.

In this context, there is a clear need for a comparative analysis that consolidates scientific and regulatory information on traditional and eco-efficient construction materials relevant to Colombia. Such an analysis can support informed decision-making by identifying trade-offs, advantages, and limitations associated with different material choices. Moreover, it can contribute to aligning construction practices with national policies on circular economy, climate change mitigation, and sustainable development [7].

This study aims to evaluate and compare traditional and eco-efficient construction materials through an integrated assessment of technical performance indicators and environmental impact metrics, with the objective of supporting sustainability-driven decision-making in civil construction. The analysis is based on a structured documentary review of the scientific literature and regulatory frameworks published between 2010 and 2025, with a specific focus on the Colombian context. By jointly considering technical, environmental, and normative dimensions, the study provides a structured and updated knowledge base to inform the selection of materials that balance structural performance with reduced environmental burden.

Unlike studies that focus exclusively on mechanical performance, environmental indicators, or specific material classes, this work contributes an integrated comparative framework that combines structural performance, environmental impact, and regulatory readiness to support sustainable material selection in the Colombian construction sector. In addition to its technical contribution, the findings highlight potential social and economic benefits, including lower demand for virgin raw materials, the strengthening of recycling value chains, and the promotion of local innovation in sustainable construction technologies.

2. Sustainability Background and Related Work

2.1. Sustainable Material Selection Criteria

Decarbonizing the construction sector is a central challenge in the global transition toward a low-carbon economy, given the sector's dependence on materials with high embodied energy and carbon intensity—particularly cement and steel. The International Energy Agency [1] emphasizes that cement manufacturing is highly energy- and emissions-intensive, largely due to clinker production. Within this context, three priority pathways are consistently highlighted for accelerating decarbonization: (i) reducing clinker content in cement, (ii) increasing the use of supplementary cementitious materials (SCMs), and (iii) improving concrete efficiency through optimized mix design and performance-based engineering. These strategies aim not only to reduce emissions but also to promote the incorporation of industrial by-products into productive cycles, reinforcing circular economy principles.

Steel is similarly positioned as a strategic material for sustainability because it can be recycled repeatedly without significant loss of performance, enabling high circularity when collection and processing systems are robust [8]. Current sectoral narratives emphasize coordinated action among industry and governments, alongside regulatory instruments that account for carbon impacts across value chains. In line with this, the Swiss Steel Group has reported that scrap-based steelmaking can substantially reduce energy demand and CO₂ emissions while remaining economically attractive, strengthening the case for recycled feedstocks as a pathway to low-carbon structural materials [9].

Within cement-based systems, partial replacement of Portland cement with SCMs remains one of the most mature and scalable approaches to reduce environmental burdens. Thomas [2] reported that replacing cement with fly ash—up to 50% under favorable curing conditions—can maintain mechanical strength while significantly lowering clinker-related CO₂ emissions. However, performance is not universal: climatic conditions, curing regimes,

and exposure environments strongly influence both early-age properties and long-term durability, underscoring the importance of context-specific evaluation rather than one-size-fits-all substitution targets.

Beyond SCMs, eco-efficient concrete and mortar formulations increasingly integrate recycled aggregates and diverse waste streams. Kou & Poon [10] investigated the durability implications of recycled coarse aggregates and addressed associated strength losses by incorporating Class F fly ash. Their experimental results showed that adding 25–35% fly ash improved the properties of mixes containing recycled aggregates, helping mitigate deficiencies in strength and durability. This work helped establish a practical direction for hybrid eco-efficient concretes that combine construction-derived recycled materials with industrial by-products.

Plastic waste has also been explored as an alternative constituent in cementitious composites. Saikia & De Brito [11] provided a comprehensive review of plastics used as aggregates, fillers, or fibers in mortars and concretes, synthesizing available experimental evidence and discussing processing methods, characterization techniques, and performance outcomes. Overall, incorporating plastics tends to reduce density and often decreases compressive strength, but may improve toughness, ductility, and thermal insulation—features that can be advantageous for lightweight and non-structural applications. Importantly, their synthesis identified persistent limitations related to performance variability and quality control and highlighted the need for standardized processing, durability studies, and robust environmental assessment.

At a higher conceptual level, Scrivener et al. [12] consolidated outcomes from an international UNEP-SBCI working group and articulated the foundations of eco-efficient cement. While acknowledging that Portland cement will remain dominant in the short term due to economics and raw material availability, they identified two technically viable mitigation strategies with near-term impact: intensive use of low-footprint SCMs and systematic optimization of clinker content in mortars and concretes. This contribution provided both a conceptual framing and a pragmatic roadmap for low-carbon cementitious systems without requiring full replacement of Portland cement in the immediate future.

Habert et al. [13] expanded this perspective by examining decarbonization strategies for cement and concrete industries through a systems lens, including global impacts beyond CO₂ such as water and energy use, and assessing technological solutions across short- and medium-term horizons. Their analysis suggested that widespread adoption of clinker optimization and mineral additions could reduce greenhouse gas emissions by up to 50%, but emphasized that meaningful transition requires coordinated action across the value chain and supportive policy incentives—reinforcing that materials innovation alone is insufficient without enabling governance and market structures.

Recent experimental evidence further supports the conditional technical feasibility of recycled aggregates. Abera [14] evaluated concretes with replacement rates ranging from 0% to 100% for both coarse and fine recycled aggregates, showing that structural performance depends strongly on replacement proportion and project-specific conditions, but that comparable strengths to conventional concrete are achievable when mix design is optimized and waste streams are appropriately selected. Bravo-German et al. [15] similarly reported acceptable mechanical behavior when replacing 50% of natural aggregate with recycled aggregate sourced from old paving blocks, indicating suitability for applications such as prefabricated elements. Collectively, these studies reinforce that sustainable material selection must balance functional performance (strength and stiffness), durability under service conditions, resource efficiency (use of recycled or by-product inputs), and environmental burden (embodied emissions and energy), while explicitly acknowledging performance trade-offs and application limits.

Finally, sustainability-oriented material selection is not only a technical challenge but also an institutional and socio-technical one. Maury-Ramírez et al. [16] proposed a circular economy model for the construction sector in Santiago de Cali (Colombia), spanning the full life cycle of building materials and proposing a portfolio of eco-efficient products integrating demolition waste, recycled aggregates, green concretes, and prefabricated modules. Their proposal linked technical strategies with an institutional framework for waste management, including the concept of a technological and environmental park to enable material valorization. Complementing this, Charef et al. [17] reviewed barriers to circular economy implementation across more than 100 studies and categorized obstacles into organizational, economic, technical, social, political, and environmental dimensions. Their synthesis shows that adoption constraints are frequently driven by regulatory inertia, limited incentives, and fragmented stakeholder coordination, rather than purely by materials performance.

2.2. Environmental Impact Assessment in Materials Engineering

Environmental impact assessment has become a central component of sustainability-driven decision-making for construction materials, with Life Cycle Assessment (LCA) serving as the dominant methodological framework for quantifying environmental burdens across the life cycle. In construction, this typically encompasses impacts from raw material extraction and processing, manufacturing, transportation, use, and end-of-life management. Relevant impact categories commonly include Global Warming Potential (GWP), energy demand, resource depletion, and waste generation, enabling comparative evaluation between traditional and eco-efficient alternatives [18,19]. Carbon footprint, in particular, is widely used as a decision metric, capturing direct and indirect greenhouse gas emissions associated with material production and deployment [20,21].

A growing body of research integrates performance-driven material development with LCA-based evaluation to show both functional and environmental gains. Khan et al. [22] formulated ultra-high-performance concrete incorporating electric arc furnace slag and recycled glass powder and combined experimental testing with LCA to quantify structural and environmental benefits. Their results indicated improvements in compressive strength and durability alongside a significant reduction in environmental impact compared to conventional UHPC, supporting the viability of industrial by-products in high-performance materials. De La Rosa et al. [23] developed eco-sustainable self-compacting concretes based on natural hydraulic lime with pozzolanic and hydraulic additions, achieving compressive strengths above 25 MPa and elastic modulus values up to 36.9 GPa, suggesting that lime-based binders can meet structural requirements while potentially reducing dependence on Portland cement.

LCA has also been applied to evaluate innovative construction solutions incorporating waste materials. Sánchez-Burgos et al. [24] conducted a comparative LCA following ISO 14044 [25] and EN 15804 [26] standards for traditional slab rehabilitation solutions versus a proposal using prefabricated mortar vaults with recycled plastic. They reported lower impacts in six out of seven environmental categories for the innovative solution, with a notable reduction in GWP100a, indicating that plastic reuse can be environmentally advantageous when embedded into functional building systems. Similarly, Peña Rey et al. [4] assessed paper mill sludge as an additive in non-structural ceramic bricks, reporting improvements in mechanical capacity and reduced environmental impact by lowering the use of virgin clays. In composite materials, Mejia-Ballesteros et al. [27] investigated dual treatments—accelerated carbonation and fiber hornification—in pine-pulp fiber cement composites, achieving substantial gains in mechanical performance and durability after

accelerated aging, while also indicating microstructural changes consistent with improved long-term stability.

Nevertheless, the literature consistently reports methodological limitations that constrain the comparability and decision usefulness of environmental assessments. Two issues are particularly recurrent, system boundary variability (e.g., cradle-to-gate versus cradle-to-grave definitions) and data quality and representativeness, especially when using generic databases for region-specific supply chains. Additionally, functional equivalence is not always ensured—materials are sometimes compared without guaranteeing comparable performance or service life. As a result, LCA-based indicators can mislead decision-making when they are interpreted independently from mechanical performance, durability, and regulatory compliance constraints. This reinforces the need for integrated evaluation frameworks that treat environmental metrics as decision variables alongside technical and contextual requirements.

2.3. Research Gap

Overall, prior research indicates substantial progress in developing eco-efficient binders, recycled-aggregate concretes, and waste-integrated construction products, and in applying LCA to quantify environmental benefits. However, existing studies rarely integrate technical performance, durability, environmental indicators, and implementation constraints within a single comparative framework that is directly applicable to engineering decisions. Much of the literature remains fragmented: performance-focused studies often lack robust environmental assessment, while LCA-focused studies may not account for functional equivalence, service life, or regulatory feasibility. This gap is especially relevant in the Colombian context, where sustainability policies and guidance documents increasingly promote circular construction, yet adoption is still limited by technical uncertainty, uneven availability of certified materials, and evolving standards.

Colombia has advanced in sustainability policy for the construction sector, emphasizing resource efficiency, responsible materials management, and life-cycle thinking. The Ministry of Environment and Sustainable Development [7] defines sustainable construction as minimizing environmental impact across the full life cycle, from raw material extraction to final waste disposal, while promoting recycling and valorization of construction and demolition waste. The national report Guidelines for Sustainable Materials [28] further supports decision-making by promoting criteria such as energy efficiency, low environmental footprint, and circularity, encouraging substitution of high-impact conventional materials with alternatives including mineral additions, recycled materials, and industrial by-products. Sectoral assessments also report growing adoption of eco-efficient practices and environmental certifications, indicating cultural and institutional progress, yet also recognizing persistent constraints such as limited availability of certified sustainable materials, informality in waste management, and insufficient technical capacity to implement circular systems at scale [29].

From a regulatory perspective, Resolution 1257 of 2021 [5] strengthened the framework for integrated construction and demolition waste management by defining responsibilities and establishing prevention, separation, reuse, and recycling directives, along with traceability mechanisms and environmental controls. These initiatives align Colombia with international decarbonization and resilience goals, but their effective implementation depends on overcoming technical, institutional, and cultural barriers—particularly those associated with clean technology adoption and coordinated value-chain action. Consequently, there is a clear need for structured, decision-oriented syntheses that consolidate dispersed evidence and evaluate traditional and eco-efficient materials through an integrated

technical–environmental–normative lens, enabling sustainable construction practices that are both technically sound and contextually feasible.

To make the contribution of this study explicit relative to the existing review literature, it is worth noting that prior syntheses concentrate on single material families (eco-efficient cements [12], alkali-activated durability [30], and plastics in cementitious composites [11]), or on single assessment dimensions (LCA methodology and applications [19,31]; circular-economy barriers [17]). None of them jointly address (i) multi-family technical performance envelopes, (ii) environmental indicators with declared boundary sensitivity, and (iii) regulatory readiness against a specific national standards framework. The present study occupies that intersection for Colombia: it does not supersede family-specific reviews in technical depth, but it provides the cross-family, decision-oriented layer, anchored in NSR-10, NTC standards, and national policy instruments, that individual reviews cannot supply. To the best of the authors' knowledge, no previous review integrates these three dimensions for the Colombian construction sector.

3. Methodology

This study was designed as a structured narrative review and comparative synthesis of secondary data reported in scientific, technical, and regulatory sources. This approach was selected because the objective was not to estimate pooled quantitative effects or conduct a meta-analysis, but to integrate heterogeneous evidence on mechanical performance, environmental impact, and regulatory readiness across multiple material families and document types. The review followed a transparent search, selection, extraction, and synthesis process to improve reproducibility while allowing critical interpretation of evidence from peer-reviewed literature, technical standards, institutional reports, and Colombian regulatory documents.

The analysis covered the period 2010–2025. Seminal pre-2010 sources were considered only when necessary to support technical definitions, historical standards, or foundational material properties. The study focused on traditional construction materials, including Portland cement, conventional concrete, structural steel, ceramic bricks, timber, and natural aggregates, as well as eco-efficient alternatives such as supplementary cementitious material-based concretes, alkali-activated binders and geopolymers, recycled aggregates, recycled-content masonry, rammed earth, *Guadua angustifolia*, and bio-based or low-carbon composites.

3.1. Search Strategy and Information Sources

The documentary search was conducted using academic databases and official technical or institutional repositories. The scientific literature was identified through Scopus, ScienceDirect, SpringerLink, MDPI, and SciELO. Complementary technical and regulatory evidence was obtained from ICONTEC standards, Colombian governmental documents, especially from the Ministry of Environment and Sustainable Development, and sectoral reports related to sustainable construction, construction and demolition waste, circular economy, and material performance.

Search terms combined concepts related to material type, technical performance, environmental assessment, and regulatory or geographical context. The main keyword groups included: “traditional building materials”, “conventional construction materials”, “eco-efficient building materials”, “sustainable construction materials”, “low-carbon materials”, “mechanical properties”, “compressive strength”, “elastic modulus”, “durability”, “carbon footprint”, “environmental impact”, “life cycle assessment”, “embodied energy”, “construction and demolition waste”, “circular economy”, “Colombia”, and “Colombian construction”.

The search strategy was adapted to the syntax and indexing structure of each database. In Scopus, two exploratory advanced searches were conducted to identify the main bodies of literature associated with conventional and eco-efficient construction materials. For traditional materials, the search combined terms related to mechanical performance, environmental impact, building materials, and conventional material families. The Scopus query was: “((TITLE-ABS-KEY (mechanical properties) OR TITLE-ABS-KEY (environmental impact)) AND (TITLE-ABS-KEY (cements) OR TITLE-ABS-KEY (steel) OR TITLE-ABS-KEY (wood) OR TITLE-ABS-KEY (timber) OR TITLE-ABS-KEY (brick))) AND PUBYEAR > 2009 AND PUBYEAR < 2026, AND (building material))”. For eco-efficient materials, the search combined technical and environmental performance terms with descriptors related to sustainable and low-impact building materials. The Scopus query was: “(TITLE-ABS-KEY (mechanical properties) OR TITLE-ABS-KEY (environmental impact) AND TITLE-ABS-KEY (eco efficient) AND TITLE-ABS-KEY (building material) AND (building materials)) AND PUBYEAR > 2008 AND PUBYEAR < 2026”. The year filter was set to cover the final review window, 2010–2025. These searches were used to map the thematic structure of the literature and guide the subsequent documentary selection; they were not treated as the final analytical corpus.

The preliminary Scopus searches retrieved broad document sets that were used for thematic mapping rather than as the final analytical corpus. The final corpus was assembled through criterion-based selection and theoretical saturation, prioritizing documents with extractable technical, environmental, or regulatory evidence directly relevant to the study objectives. Therefore, the search results were used to guide evidence identification and thematic organization, while the final synthesis was based on documents that met the eligibility criteria and provided traceable information for comparison.

Figure 1 summarizes the document identification and selection workflow. Candidate documents entered the review through three routes: (i) exploratory database searches, whose Scopus queries are reported verbatim above (executed on November 2025, retrieving approximately 58,016 and 374 records, respectively; re-execution of the same queries in July 2026 returned $\approx 71,229$ and 385 records, respectively, consistent with the continued indexing of 2025 publications) and which were used for thematic mapping rather than as a closed sampling frame; (ii) purposive identification of applicable standards, codes, and policy instruments in official repositories (ICONTEC catalogue, MinAmbiente, Min-Vivienda, INVIAS), selected by direct relevance to the material families under study; and (iii) citation chaining from key reviews and institutional reports. All candidate documents were then assessed against the eligibility criteria of Section 3.2, and selection proceeded under theoretical saturation, prioritizing documents with extractable and traceable technical, environmental, or regulatory evidence. Consistent with the structured narrative design, intermediate screening counts were not exhaustively logged; instead, transparency is provided at the two ends of the process: the identification stage is reproducible through the reported queries and individually cited normative documents, and the final corpus ($n = 103$: 54 peer-reviewed journal articles, 13 conference papers, 7 books or book chapters, 9 technical standards and codes, 5 regulatory and policy instruments, and 15 institutional reports) is fully traceable through the reference list.

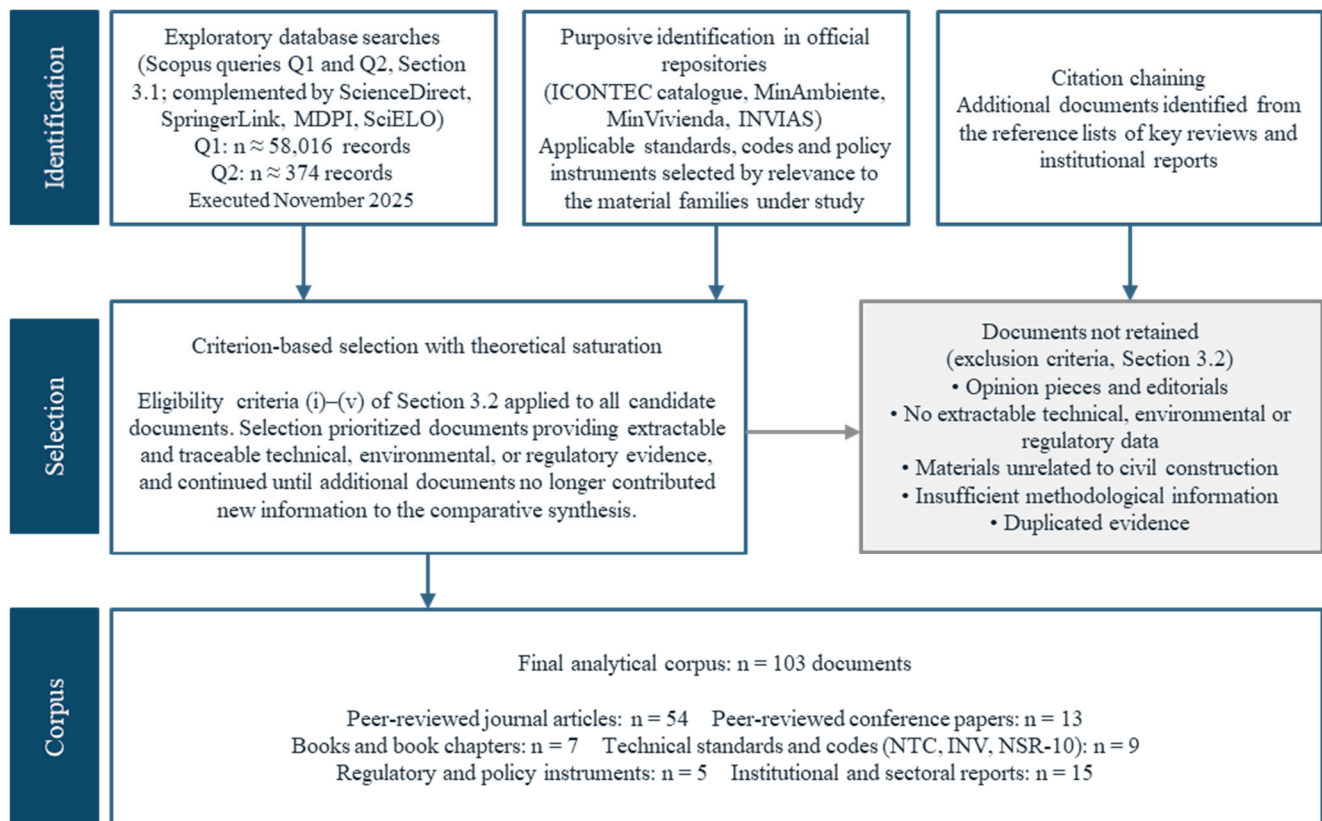


Figure 1. Workflow of the selection of structured documents.

3.2. Eligibility Criteria

Documents were included when they met the following criteria: (i) publication between 2010 and 2025, except for seminal or normative sources required for technical context; (ii) academic, technical, regulatory, governmental, or institutional provenance; (iii) availability of quantitative or clearly traceable evidence on at least one technical, environmental, material, or regulatory variable; (iv) relevance to construction materials used in structural, non-structural, prefabricated, or infrastructure applications; and (v) full-text availability for data extraction. Documents were excluded when they consisted only of opinion pieces, editorials, or non-traceable qualitative claims; lacked technical, environmental, or regulatory information relevant to the study; were duplicates; addressed materials unrelated to civil construction; or did not provide sufficient methodological information to interpret the reported data.

3.3. Materials and Application Context

This research compares traditional and eco-efficient (alternative) construction materials commonly used in civil works, with a focus on applications where functional requirements—structural or non-structural—must be satisfied under sustainability constraints. Traditional materials considered in the documentary corpus include Portland cement, conventional concrete, structural steel, ceramic bricks, and natural aggregates. Eco-efficient materials include, among others, concretes incorporating supplementary cementitious materials (SCMs) (e.g., fly ash, and slag), recycled aggregates derived from construction and demolition waste (C&DW), cementitious composites incorporating industrial by-products, and prefabricated products with recycled or low-impact content.

To ensure comparability across studies, materials were interpreted through the lens of functional requirements, including minimum mechanical performance (e.g., compressive strength and stiffness), durability expectations under service conditions, and applicability

in typical construction settings. Sustainability relevance was defined in terms of potential reductions in embodied emissions and energy demand, decreased reliance on virgin resources, and improved circularity through the incorporation of waste streams or industrial residues. Where applicable, the relevance of each material class to the Colombian construction context was explicitly recorded, including reported barriers, local feasibility, and regulatory considerations.

3.4. Data Extraction and Harmonization

For each eligible document, quantitative and contextual information was extracted using a standardized data-recording template. Extracted fields included document type, full bibliographic reference, year and country of publication, material type and composition, construction application (structural, non-structural, or prefabricated), reported technical indicators (e.g., compressive strength and elastic modulus), environmental indicators (e.g., GWP and embodied energy), system boundaries used in environmental assessments, and reported limitations or barriers to implementation.

To enable comparative analysis, data were harmonized by converting units where necessary and annotating differences in test conditions or assessment assumptions. When methodological heterogeneity prevented direct numerical comparison, results were retained for qualitative interpretation and explicitly flagged. This approach improved consistency in the comparative synthesis while preserving the contextual information needed to interpret heterogeneous sources.

3.5. Technical Performance Assessment

The technical assessment is based on quantitative indicators extracted from the selected documentary sources. Core technical indicators include compressive strength (MPa), elastic modulus (GPa), and density (kg/m^3). Where studies reported additional performance aspects (e.g., durability-related outcomes), these were recorded as complementary information to support interpretation but were not forced into numerical comparison when methodological heterogeneity prevented fair aggregation.

Data sources comprised peer-reviewed journal articles, technical reports, and official standards or institutional documents. Because the study relies on secondary data, assumptions were applied to harmonize evidence across heterogeneous reporting practices. These include: (i) prioritizing reported values derived from standardized testing protocols when available; (ii) recording the stated test conditions and material composition to contextualize results; and (iii) treating performance outcomes as comparable only when the material function and application class were sufficiently aligned (e.g., structural vs. non-structural applications). When units or reference conditions differed across sources, values were converted and annotated to preserve traceability and reduce misinterpretation.

3.6. Environmental Impact Indicators

Environmental performance was assessed using quantitative indicators reported in the reviewed literature and regulatory sources. The primary environmental indicators extracted were:

- Carbon footprint/Global Warming Potential (GWP), reported as $\text{kg CO}_2\text{-eq}$ per functional unit (commonly per m^3 of material or per ton, depending on the study);
- Embodied energy, reported as MJ/kg (or equivalent energy units);
- Relative emissions reduction, reported as % compared with conventional reference materials, when explicitly provided by the source.

A key methodological priority was documenting the scope and system boundaries used in environmental assessments, since these strongly affect comparability. When avail-

able, the study recorded whether LCA results were reported under cradle-to-gate, cradle-to-site, or cradle-to-grave boundaries, along with the stated functional unit and major assumptions. Studies adopting recognized standards (e.g., ISO-based LCA reporting) were flagged accordingly to support quality assessment. When boundary conditions were unclear or inconsistent, results were retained for qualitative interpretation but were treated cautiously in quantitative synthesis.

The environmental indicators reported in this study were extracted from heterogeneous literature sources employing different functional units, system boundaries, geographical contexts, and life-cycle assessment (LCA) assumptions. Consequently, the values presented should be interpreted as representative ranges rather than directly comparable measurements. To improve consistency, emphasis was placed on the direction and magnitude of reported impacts (e.g., relative reductions in CO₂ emissions or energy demand) rather than on exact numerical equivalence. Where possible, values were normalized to commonly reported units or expressed as percentage changes relative to conventional reference materials.

3.7. Comparative Sustainability Assessment Framework

To deliver a decision-oriented comparison, technical and environmental indicators were integrated into a structured evaluation framework designed to support sustainable material selection under real-world constraints. The framework is built on four principles: indicator harmonization, comparative logic, decision relevance, and traceability.

Harmonization of indicators. Because the indicators extracted from the literature were reported using different units, methodologies, and assessment contexts (e.g., MPa, kg CO₂-eq, MJ/kg, or percentage reductions), direct numerical comparisons were not always possible. Therefore, the indicators were harmonized through a structured synthesis approach that emphasized their relative performance, reported ranges, and direction of impact rather than exact numerical equivalence. This approach enabled the integration of technical, environmental, and regulatory evidence into a common comparative framework while preserving the context and assumptions of the original studies.

Comparative logic. The comparison was conducted between (i) traditional materials and (ii) eco-efficient alternatives, respecting functional equivalence to the extent permitted by the documentary evidence. Technical indicators were treated as performance constraints (materials must meet minimum functional thresholds), while environmental indicators were treated as sustainability objectives (materials should minimize environmental burden). Where the evidence supported it, the framework enabled identification of trade-offs (e.g., environmental gains associated with modest reductions in compressive strength) and the classification of materials into performance–impact profiles.

Assignment criteria for qualitative ratings. To ensure that the qualitative ratings used in the decision matrices (applied to Tables 5 and 8) are transparent and reproducible, each dimension was rated on a three-level ordinal scale (High/Medium/Low) using the operational criteria defined in Table 1. Ratings were assigned by confronting the harmonized evidence extracted for each material family against these criteria; where the evidence for a family spanned two levels, an interval rating (e.g., Medium–High) was recorded rather than forcing a single level. The criteria combine quantitative anchors, where the literature supports them (e.g., reported CO₂-eq reduction ranges), with verifiable qualitative conditions (e.g., existence of an applicable Colombian technical standard). Ratings were assigned by the first author and independently verified by the co-authors; discrepancies were resolved by consensus.

Table 1. Criteria for High/Medium/Low ratings used in Tables 5 and 8.

Dimension	High	Medium	Low
Technical feasibility	Structural-grade performance demonstrated at full scale; behavior codified in current Colombian standards (NSR-10, NTC) or directly covered by existing specifications; low sensitivity to execution quality.	Structural-grade performance reported in peer-reviewed experimental studies, but conditional on strict quality control, curing, or mix-design governance; partial or indirect coverage by standards; pilot-scale applications documented.	Evidence limited to laboratory scale or non-structural applications; high performance variability across studies; no applicable standard or certification pathway.
Environmental advantage	Consistently reported reduction in embodied CO ₂ -eq greater than 50% relative to the conventional functional equivalent, or net biogenic carbon storage, across at least two independent sources with comparable boundaries.	Reported CO ₂ -eq or embodied-energy reductions between 20% and 50%, or larger reductions reported under boundary or allocation assumptions that limit generalization.	Reported reductions below 20%, negligible, or highly dependent on unverified assumptions (e.g., zero-burden allocation of by-products, uncertain end-of-life credits).
Evidence quality	Multiple (≥ 3) independent peer-reviewed sources with consistent results; standardized test methods; environmental data reported under declared ISO-based system boundaries.	Two or more sources with broadly consistent direction of results but heterogeneous methods, functional units, or boundaries; a single high-quality source complemented by technical reports.	Single-source evidence, grey literature only, undeclared boundaries or test conditions, or contradictory results across sources.
Colombia readiness	Applicable Colombian standard or code pathway in force (NTC/NSR-10/INVIAS); established national supply chain; documented commercial or institutional use in Colombia.	Emerging regulatory recognition (partial standards, pilot regulations, regional acceptance) or documented Colombian pilot/academic projects; supply chain exists but is regional or fragmented.	No applicable Colombian standard; adoption would require the alternative-materials approval route (Law 400 of 1997, Art. 8–14); no documented local supply chain or field experience.

A High rating requires that all conditions listed for that level are met; when a family satisfies the conditions of adjacent levels only partially, an interval rating (e.g., Med–High) is assigned rather than forcing a single level.

Decision relevance. To ensure that the synthesis supports engineering and policy decisions, the framework incorporates a normative dimension capturing whether the material is (at least in principle) compatible with the Colombian regulatory and technical context. This includes recording reported acceptance or constraints associated with Colombian standards and policies. The output of the integrated framework is a technical–environmental comparative matrix that consolidates evidence into a decision-support format suitable for engineers, designers, and regulators.

Traceability and transparency. Each data point included in the comparative matrices is linked to the corresponding literature source, including document type, publication year, application context, and relevant methodological considerations reported by the original authors. This approach enhances transparency and allows readers to trace the origin of the evidence used in the synthesis.

3.8. Validity, Reliability, and Methodological Limitations

Content validity was strengthened by prioritizing the indexed scientific literature, official technical standards, and institutional reports with recognized methodological rigor. Reliability was supported by documenting the selection criteria, data extraction procedures, and normalization rules used to organize and compare the evidence. This structured documentation was intended to improve transparency and consistency in the synthesis

process and to reduce, although not eliminate, subjective bias in the interpretation of heterogeneous sources.

Nevertheless, various limitations must be acknowledged. The accuracy and comparability of the synthesized data depend on the quality and consistency of the original sources. Variations in experimental protocols, functional units, geographical contexts, life-cycle inventory assumptions, and LCA system boundaries introduce uncertainty that cannot be fully eliminated in a documentary study. In addition, because the analysis is based exclusively on secondary data, the study does not exert direct control over testing conditions or measurement procedures reported in the literature. This study was not designed as a formal systematic review or meta-analysis; therefore, PRISMA-based screening procedures and quantitative risk-of-bias assessments were not performed.

A structured narrative design remains exposed to selection bias, since the final corpus is assembled by criterion-based judgment rather than exhaustive screening. Three safeguards were adopted to mitigate this risk: (i) the database queries were defined a priori and are reported verbatim in Section 3.1, making the identification stage reproducible; (ii) evidence was deliberately triangulated across three source types (peer-reviewed literature, technical standards, and regulatory or institutional documents), so that no single publication channel determined the conclusions; and (iii) for each material family, sources reporting unfavorable or conditional performance were actively sought and retained (e.g., strength losses in recycled-aggregate concretes, durability concerns in bio-based materials), and these constraints are reported explicitly in Tables 3 and 5. Residual bias cannot be excluded, particularly toward the published literature (publication bias) and toward materials with an active research community; conclusions should be read with this limitation in mind.

3.9. Ethical Considerations

This study does not involve human participants, animals, or primary experimental testing and therefore does not require approval from an ethics committee. Ethical research practices were nevertheless observed throughout the study, including the proper citation of all sources in accordance with the proper citation of all sources, respect for intellectual property rights, and adherence to the access conditions of consulted documents. Transparency was maintained at each methodological stage to avoid selective reporting and to ensure that the synthesis accurately reflects the available evidence.

4. Results

This section reports the evidence synthesized from the documentary review (2010–2025) comparing conventional and eco-efficient materials relevant to civil construction in Colombia. Results are organized as (i) technical performance, (ii) environmental impacts, and (iii) integrated trade-offs and Colombia-specific readiness, consistent with the decision-oriented framework introduced in Section 3.

4.1. Technical Performance Results

4.1.1. Conventional Materials: Reference Performance Envelopes

Across the reviewed sources, conventional materials remain dominant because their mechanical behavior is well bounded, standardized, and code-compatible [32,33] (Table 2). Portland cement-based concretes typically achieve 25–50 MPa compressive strength in conventional applications and exceed 70 MPa in high-strength mixes depending on w/c ratio, curing, and aggregate characteristics [34–38]. Their elastic modulus commonly falls in the range of 20–35 GPa, and their low tensile capacity reinforces the need for steel in tension-controlled limit states.

Structural steel exhibits the highest stiffness and ductility among the evaluated materials, with yield strengths commonly reported in the 250–400 MPa range for typical grades and tensile strengths frequently >400 MPa, with $E \approx 200$ GPa [39–41]. Ceramic bricks show compressive strengths typically in the range of 7–20 MPa, governed by clay composition, porosity, and firing quality [22,42–44]. Timber exhibits strong strength-to-weight behavior but anisotropy and moisture sensitivity; reported modulus values commonly lie within the range of 8–16 GPa and compressive strength parallel to the grain in the range of 20–50 MPa [45–47].

Table 2. Mechanical performance ranges of conventional materials and primary technical dependencies (2010–2025). Typical ranges for compressive strength, modulus, and key constraints affecting performance and applicability (mix design/curing for concrete; grade and ductility for steel; porosity/firing for brick; moisture/directionality for timber).

Material	Mechanical Property	Unit	Typical Range	Technical Remarks	References
Portland cement-based concrete	Compressive strength	MPa	25–50 (conventional); >70 (high-performance)	Strongly dependent on water–cement ratio, curing regime, and aggregate type	[34–38]
	Tensile strength	MPa	2–5	Low tensile capacity; requires steel reinforcement	
	Flexural strength	MPa	3–7	Influenced by mixed homogeneity and compaction quality	
	Elastic modulus	GPa	20–35	Indicator of stiffness; increases with lower w/c ratio	
	Durability	—	High	Good resistance to chemical attack and thermal variation when properly designed	
Structural steel	Yield strength	MPa	250–400 (S275–S355)	Enhanced through alloy control and thermal treatment	[39–41]
	Tensile strength	MPa	400–600	High ductility prior to failure	
	Elastic modulus	GPa	200–210	Practically constant, independent of alloying	
	Hardness	—	Medium–high	Increases with carbon content and quenching	
	Toughness/ductility	—	High	Allows plastic deformation without brittle fracture	
Ceramic brick	Compressive strength	MPa	7–20	Highly dependent on firing temperature and porosity	[22,42–44]
	Density	kg/m ³	1600–2000	Positively correlated with compressive strength	
	Water absorption	%	10–20	High values reduce durability and mechanical stability	
Structural timber	Durability	—	Medium	Controlled by raw material quality and sintering conditions	[45–47]
	Compressive strength (parallel to grain)	MPa	20–50	Strongly affected by species, moisture content, and fiber orientation	
	Flexural strength	MPa	40–100	Excellent strength-to-weight ratio	
	Elastic modulus	GPa	8–16	Lower stiffness than concrete and steel; anisotropic behavior	
	Shear strength	MPa	4–10	Critical for joints and beam performance	
	Durability	—	Variable	Sensitive to moisture, biological attack, and protective treatments	

4.1.2. Eco-Efficient Materials: Performance and Applicability Constraints

Evidence indicates that several eco-efficient families can achieve structural-grade performance, but applicability is conditional on durability confidence, quality control, and standardization maturity (Table 3). SCM-based concretes and alkali-activated/geopolymer binders frequently report compressive strengths ranging from ~40 MPa to >100 MPa, with upper ranges reaching ~170 MPa under optimized formulations and curing regimes [48,49]. Improvements in resistance to chloride ingress and sulfate exposure are repeatedly reported when chemistry and curing are controlled [50–54].

Recycled aggregate concretes are viable at moderate-to-high replacement ratios, although reductions in strength or stiffness may occur unless aggregate quality, grading, and supplementary binders are managed [48]. By contrast, bio-based and insulation-oriented materials (e.g., mycelium/PLA foams and natural-fiber panels) are consistently positioned as non-structural, typically reporting compressive strengths ~2–5 MPa alongside low thermal conductivity values (0.026–0.05 W/m·K) [55,56]. Colombian-context natural materials (rammed earth and guadua) are relevant for low-rise or specialized systems, with performance highly dependent on execution quality and protective treatments [57,58]. Self-healing/nano-modified concretes primarily target service-life extension (crack control and reduced maintenance) rather than simply maximizing initial strength [59,60].

The durability signals summarized in Table 3 are examined in Section 5.5, where service life and end-of-life are treated as environmental variables rather than purely technical attributes.

Table 3. Technical performance and application class of eco-efficient material families (2010–2025). Consolidated ranges and application suitability (structural vs. non-structural), including key constraints (curing sensitivity, precursor availability, variability, and durability considerations).

Material Family	Typical Application Class	Technical Performance (What the Literature Consistently Reports)	Durability/Service-Life Signals	Main Constraints/Barriers	Representative Sources
SCM-based concretes (fly ash, GGBFS, etc.)	Structural/non-structural	Comparable compressive performance to conventional concrete when mix design and curing are optimized; stiffness and early-age strength depend on substitution level and SCM type.	Often improved resistance to aggressive exposure when permeability is reduced; performance depends on curing and SCM chemistry.	Local availability, variability of SCMs, acceptance in specifications and procurement.	[12,13]
Alkali-activated/geopolymers (AAMs)	Structural (select)/non-structural	High strength potential reported under controlled activation; performance sensitive to activator type, precursor chemistry, and curing regime.	Durability depends strongly on binder chemistry (e.g., Si/Al ratio) and exposure type; long-term field evidence still limited.	Lack of standardization, handling/availability of activators, variability in precursor sources.	[30,49]
Recycled aggregate concrete (RCA)	Structural (limited)/non-structural	Strength and modulus can decrease with high replacement unless grading, pre-treatment, and SCM co-use are applied; variability is a recurring issue.	Durability performance is mixed; can be improved by SCMs and controlling absorption/permeability.	Quality control, heterogeneity of recycled streams, inconsistent standards for structural use.	[10,14,15]
Recycled-content masonry (eco-bricks, recycled fillers)	Mostly non-structural	Often reduced density and compressive resistance versus conventional bricks, with potential gains in toughness/ductility depending on waste type and processing.	Water absorption and long-term weathering are frequent concerns; performance depends on manufacturing consistency.	Product certification, performance variability, limited structural acceptance.	[4,11]
Bio-based insulation/composites (mycelium, PLA foams, natural fibers)	Non-structural	Designed primarily for thermal/weight performance; mechanical capacity generally adequate for insulation boards and light components.	Moisture and fire performance require protective design; durability still under optimization.	Fire/moisture protection requirements, standardization and market maturity.	[56,61]
Rammed earth	Low-rise/vernacular	Structural viability depends on soil gradation, compaction, and stabilization; used primarily in low-rise walls.	Erosion/moisture durability is execution-dependent; stabilizers can improve performance.	Execution sensitivity, limited codification, contractor skill and acceptance.	[57]
Guadua structural systems	Low–mid-rise (code-governed)	Strong strength-to-weight and good seismic behavior when designed and detailed properly.	Biodeterioration risk requires treatment; durability depends on detailing and exposure control.	Standardization, treatment impacts, acceptance in mixed systems.	[58,62,63]
Smart/durability-enhancing concretes (self-healing/nano-modified)	Structural support	Performance benefit is primarily crack control and permeability reduction; strength gains are not always the main target.	Potential for maintenance reduction and service-life extension, but results depend on additive type and dosage.	Cost, dispersion/curing control, footprint of additives, limited harmonized LCA.	[59,60]

4.2. Environmental Impact Results

4.2.1. Conventional Materials: Dominant Impact Hotspots

Portland cement consistently exhibits high embodied CO₂ due to clinker production, combining process emissions from limestone decarbonation and fuel emissions from high-temperature kilns; representative values frequently reported are on the order of ~0.9 t CO₂ per ton of cement [1,64,65]. Steel shows strong dependence on production route: BOF (primary) pathways are typically high-emission, while EAF (scrap-based) pathways can substantially reduce emissions, underlining recycling as a major mitigation lever [8,66,67]. Ceramic brick impacts concentrate in firing and are amplified by air-quality emissions in low-efficiency or informal kilns [68,69]. Timber tends to show a comparatively favorable profile when sourced sustainably, though outcomes are contingent on traceability and forestry management [70,71]. The environmental indicators summarized in this section originate from studies employing different functional units, geographical contexts, and LCA system boundaries. Consequently, the reported values should be interpreted as representative ranges that illustrate general trends rather than directly comparable emission

factors. Table 4 provides a comparative synthesis of key environmental impact indicators for conventional construction materials.

Table 4. Environmental impact profile of conventional materials (qualitative synthesis, 2010–2025). Comparative summary of CO₂ intensity, energy demand, resource pressure, and recyclability drivers for cement, steel, brick, and timber.

Material	CO ₂ Emissions Intensity	Resource Consumption	Energy Demand	Health and Air Quality Impacts	Recycling Potential	References
Portland cement	Very high (~0.9 t CO ₂ /t)	High (limestone, clay)	Very high	Moderate (dust, NO _x , SO ₂ exposure during production)	Low	[64,65,72,73]
Structural steel	High (~1.8 t CO ₂ /t, BOF route)	High (iron ore, coal)	Very high	Moderate (particulate matter, industrial emissions)	High	[66,67,72,74]
Ceramic brick	Moderate (200–400 kg CO ₂ /t)	Moderate (clay extraction)	High	High (particulate matter, SO ₂ , NO _x during firing)	Low	[68,69,75]
Structural timber	Low (carbon storage effect)	Low (sustainably managed forestry)	Low	Low	Moderate	[70,71,76]

4.2.2. Eco-Efficient Materials: Reported Reductions and Boundary Sensitivity

Eco-efficient options achieve environmental gains primarily through clinker substitution, industrial by-product valorization, and recycled-content deployment. Reported CO₂ reductions for geopolymers/alkali-activated binders commonly fall within ~60–85% relative to conventional cement-based baselines under comparable functional assumptions, while SCM concretes frequently reduce embodied energy by ~26–40% depending on substitution ratios and boundary definitions [12,31]. Recycled-content pathways provide additional benefits by reducing virgin extraction and diverting waste from disposal [77]. Bio-based materials may show very low or even net-negative footprints depending on accounting choices, end-of-life assumptions, and the treatment of biogenic carbon [56]. For Colombian natural materials, case-based results indicate substantially lower embodied emissions per unit area for guadua housing relative to conventional masonry, and reduced footprints for optimized rammed-earth systems relative to less controlled approaches [57,58]. For durability-enhancing smart materials, the environmental case often hinges on lifetime extension, not only initial embodied impacts [78,79].

4.3. Integrated Trade-Offs and Decision Relevance

When interpreted jointly, the evidence yields three decision-relevant patterns:

- Structural-grade decarbonization is most consistently supported by cementitious substitution strategies (SCMs and alkali-activated binders), provided that curing, material supply, and durability risks are controlled.
- Recycled aggregates and recycled-content products offer meaningful environmental gains but may introduce variability and performance penalties without strict quality and mix design governance.
- Bio-based and natural materials deliver strong footprint advantages but remain predominantly non-structural (or low-rise/specialized structural), where moisture/fire performance and long-term durability are recurrent barriers.

These results reinforce the central methodological premise of this study: performance-only comparisons are insufficient because they ignore embodied burdens that dominate sustainability outcomes for high-volume materials, while environment-only assessments can mislead if functional equivalence and code compliance are not enforced. A decision-relevant comparison therefore requires the integrated logic proposed in Section 3.4. Table 5 presents an integrated decision matrix linking functional role, technical feasibility, environmental advantage, and adoption barriers for major construction material families.

Table 5. Decision matrix linking application class, technical feasibility, environmental advantage, and adoption barriers (2010–2025). Integrated synthesis mapping each material family to (i) functional role (structural/non-structural), (ii) technical feasibility and constraints, (iii) direction/magnitude of environmental benefit, and (iv) dominant barriers (standardization, data quality, supply chain, durability, and regulatory acceptance). Ratings assigned according to the operational criteria defined in Table 1.

Material Family	Functional Role	Technical Feasibility (High/Med/Low)	Environmental Advantage (High/Med/Low)	Evidence Quality (High/Med/Low)	Main Trade-Off(s)	Colombia Readiness (High/Med/Low)	Key Enabling Conditions
Portland cement/conventional concrete (baseline)	Structural	High	Low	High	—	High	existing supply + standards
SCM-based concrete	Structural	Med–High	Med–High	Med–High	curing/variability vs. CO ₂ reduction	Med	supply chain + performance specs
AAMs * / geopolymers	Structural (select)	Medium	High	Medium	standardization vs. footprint benefits	Low–Med	codes, durability datasets
Recycled aggregates	Both	Medium	Medium	Medium	variability vs. resource savings	Med	logistics + QA/QC
Eco-bricks/recycled masonry	Non-structural	Medium	Medium	Medium	strength/absorption vs. emissions savings	Med	product standards + certification
Bio-based insulation	Non-structural	Medium	High	Medium	durability/fire vs. low footprint	Low–Med	protection systems + standards
Rammed earth	Low-rise	Medium	Medium–High	Medium	execution sensitivity vs. low footprint	Med (regional)	stabilization + guidance
Guadua systems	Low–mid rise	Medium	High	Medium	durability treatments vs. footprint savings	Med	NSR acceptance + QA/QC
Self-healing/nano concretes	Structural support	Medium	Case-dependent **	Low–Med	initial footprint vs. lifetime benefits	Low	service-life models + LCA consistency

* Rated on the binder-level comparison basis dominant in the literature (60–85%, Section 4.2.2); at the concrete level the range is wider and formulation-dependent (Section 4.3.1). ** Where the environmental outcome depends on the service-life scenario rather than on production burdens, no fixed level is assigned (see Section 5.5).

4.3.1. Illustrative Application of the Framework: Structural Concrete for Social Housing in Colombia

To illustrate how the integrated framework operates on a concrete decision, this section develops a traceable numerical comparison for a recurrent Colombian application: one cubic meter of structural concrete with a specified compressive strength of $f'_c = 28$ MPa, a typical requirement for low- and mid-rise social housing structures under NSR-10, Title C [80]. Three functionally equivalent options are compared under a declared cradle-to-gate boundary: (i) a conventional mix based on ordinary Portland cement (OPC); (ii) the same mix with 30% of the cement mass replaced by fly ash (FA); and (iii) a fly-ash-based geopolymer concrete of equivalent strength class. All assumptions, data sources, and calculation steps are stated explicitly so that the example can be independently reproduced.

Assumptions and input data. A representative mix design for $f'_c = 28$ MPa is adopted, consistent with conventional proportioning practice (ACI 211.1-type) as follows. For a 75–100 mm slump and a 19 mm nominal maximum aggregate size, a water content of 185 kg/m³ is selected; a water-to-cement ratio of ≈ 0.53 , appropriate for the target strength without admixtures, then yields a cement content of $185/0.53 \approx 350$ kg/m³. The absolute volumes of cement ($350/3150 = 0.111$ m³), water (0.185 m³), and entrapped air ($\approx 2\%$, 0.020 m³) total 0.316 m³, leaving 0.684 m³ for aggregates; at a typical aggregate specific gravity of 2.65, this corresponds to $0.684 \times 2650 \approx 1800$ kg/m³ of total aggregates, distributed as ≈ 1050 kg of coarse and ≈ 750 kg of fine aggregate according to the standard coarse-aggregate volume factor for this maximum size and sand fineness. The resulting theoretical fresh density—the sum of all constituent masses—is $350 + 185 + 750 + 1050 = 2335$ kg/m³, within the 2200–2400 kg/m³ range of normal-weight concrete, which serves as an internal plausibility

check of the proportioning. The cradle-to-gate emission factors are: 0.90 kg CO₂-eq per kg of cement, corresponding to the representative intensity synthesized in Table 4 [64,65,72,73]; 0.006 kg CO₂-eq per kg of aggregates, within the ≈ 0.005 –0.01 kg CO₂-eq/kg range reported for aggregate extraction, crushing, and screening in standard embodied-carbon inventories [81]; and 0.02 kg CO₂-eq per kg of fly ash under the zero-burden (waste) allocation convention, in which the by-product carries only its conditioning and transport emissions [82]. Reported values range from ≈ 0.008 kg CO₂-eq/kg for minimally processed ash [81] to ≈ 0.027 kg CO₂-eq/kg when collection, processing, and haulage are included [83]. The contribution of mixing water is negligible (< 0.5 kg CO₂-eq/m³) and is omitted; transport of materials to the batching plant and all downstream stages are excluded by the declared cradle-to-gate boundary. For the fly-ash mix, a 30% mass replacement is adopted because it is widely reported to preserve the 28-day design strength under adequate curing, with replacement levels of up to 50% feasible under favorable conditions [2,12]; 30% is therefore a conservative and code-compatible choice, since NTC 121 admits blended and added cements under performance-based specification.

Option 1—conventional OPC concrete. The embodied carbon is computed as the sum of each constituent mass multiplied by its emission factor:

$$EC(\text{conv}) = 350 \text{ kg} \times 0.90 + 1800 \text{ kg} \times 0.006 = 315.0 + 10.8 \approx 325 \text{ kg CO}_2\text{-eq/m}^3$$

The binder alone contributes 315 of 325 kg, i.e., approximately 97% of the cradle-to-gate footprint. This dominance—a direct consequence of limestone calcination and kiln combustion in clinker production—explains why clinker substitution is the single most effective decarbonization lever for structural-grade concrete, consistent with Section 4.3.

Option 2—OPC with 30% fly ash. Replacing 30% of the cement mass yields 245 kg of OPC and 105 kg of FA per cubic meter:

$$EC(\text{FA30}) = 245 \times 0.90 + 105 \times 0.02 + 1800 \times 0.006 = 220.5 + 2.1 + 10.8 \approx 235 \text{ kg CO}_2\text{-eq/m}^3$$

The resulting reduction is $(325 - 235)/325 = 28\%$ relative to the conventional option. Note that the reduction (28%) is slightly smaller than the substitution level (30%): the fly ash is not entirely burden-free under the adopted convention, and the aggregate contribution is common to both options. This internal consistency check is itself informative, substitution benefits scale almost, but not exactly, linearly with replacement level.

Option 3—fly-ash geopolymers concrete. For the geopolymer option, a closed-form calculation is deliberately not presented, because the footprint is dominated by the alkaline activators, whose type, dosage, and solids content vary widely across formulations. In typical mixes of equivalent strength class, the binder system comprises roughly 400 kg/m³ of low-burden precursor (fly ash) activated with sodium silicate and sodium hydroxide at combined dosages on the order of 40–100 kg/m³ (dry basis), and higher in activator-rich formulations [54,83]. Reported emission factors are ≈ 1.1 –1.5 kg CO₂-eq/kg for sodium silicate on a solids basis (≈ 1.22 for manufacturing plus ≈ 0.29 for transport) and ≈ 0.9 –1.9 kg CO₂-eq/kg for sodium hydroxide from the chlor-alkali process [83,84]; in alkali-activated concretes, the activators dominate the footprint and contribute on the order of 50–150 kg CO₂-eq/m³. Adding precursor conditioning and the common aggregate contribution yields a representative cradle-to-gate range of 120–190 kg CO₂-eq/m³ for ambient-cured mixes, i.e., reductions of approximately 42–63% relative to the conventional option— $(325 - 190)/325 = 42\%$ and $(325 - 120)/325 = 63\%$ —consistent with the ≈ 43 –45% reductions computed in dedicated LCAs of fly-ash geopolymer concrete [84]. Estimates as low as ≈ 9 –10% have nonetheless been reported when high activator dosages, elevated-temperature curing, and raw-material transport are included within the boundary [83], reinforcing that the geopolymer advantage is strongly formulation- and boundary-dependent, one further reason why this option is rated Medium for evidence quality in Table 5.

Functional-unit consistency. These concrete-level reductions (42–63% per m³) are fully consistent with—but numerically lower than—the binder-level reductions of 60–85% cited in Section 4.2.2. The difference is one of functional unit: the binder-level figures compare one tonne of geopolymer binder against one tonne of Portland cement (≈ 130 – 360 vs. ≈ 900 kg CO₂-eq/t), whereas the per-cubic-meter comparison accounts explicitly and completely for the activator burden and includes the aggregate contribution common to all options. The upper end of the binder-level range additionally reflects formulations with optimistic activator accounting. This distinction illustrates, within the example itself, why functional-unit declaration is indispensable for valid comparisons (Section 3.5).

Sensitivity to allocation. The 28% reduction of Option 2 is conditional on the zero-burden convention for fly ash. Under economic allocation—assigning to the ash a share of the coal power plant’s emissions proportional to its economic value—the fly-ash factor rises to approximately 0.10–0.20 kg CO₂-eq/kg; recomputing with a mid-value of 0.15 gives $105 \times 0.15 = 15.8$ kg, a total of ≈ 247 kg CO₂-eq/m³, and a reduction of $\approx 24\%$ instead of 28%. Under mass-based allocation the burden assigned to the ash can become large enough to eliminate most of the benefit. The same sensitivity propagates to the geopolymer option, whose precursor is also fly ash. These dependencies are developed in Section 4.3.2; within this example they show that the ranking of Options 1 and 2 is robust across allocation conventions, but the magnitude of the advantage is not.

Beyond the numbers, the example exposes the trade-off structure that motivates this study: the environmental ranking inverts the regulatory-readiness ranking. The option with the largest reported reductions (geopolymer) is also the one facing the highest normative barrier in Colombia, as it is not covered by prescriptive standards and would currently require the alternative-materials approval pathway established by Law 400 of 1997 [85], whereas the moderate-reduction option (30% FA) is immediately deployable under NTC 121 performance specifications. The values in Table 6 are illustrative rather than design values: they inherit the boundary, functional-unit, and allocation caveats of Sections 3.5 and 4.3.2, and project-level results will vary with mix design, transport distances, cement chemistry, and curing. The purpose of the example is to demonstrate, end to end, how the framework converts heterogeneous literature evidence into a traceable, decision-oriented comparison for a specific Colombian application.

Table 6. Illustrative cradle-to-gate comparison of three structural concrete options ($f'_c = 28$ MPa, 1 m³), Colombian context. All values computed as described in the text; totals rounded to the nearest 5 kg.

Item	Conventional OPC Concrete	OPC + 30% Fly Ash	Fly-Ash Geopolymer
Mix basis (kg/m ³)	350 OPC + 1800 aggregates + 185 water	245 OPC + 105 FA + 1800 aggregates + 185 water	≈ 400 FA precursor + 40–100 activators + aggregates
Embodied CO ₂ of binder (kg CO ₂ -eq/m ³)	315.0	222.6 (220.5 OPC + 2.1 FA)	≈ 110 – 180 (activator-dominated)
Embodied CO ₂ of aggregates (kg CO ₂ -eq/m ³)	10.8	10.8	10.8
Total (kg CO ₂ -eq/m ³ , cradle-to-gate)	≈ 325	≈ 235	≈ 120 – 190
Reduction vs. conventional	—(baseline)	$\approx 28\%$	≈ 42 – 63%
Sensitivity to FA allocation	n/a	$\approx 24\%$ under economic allocation; benefit largely eliminated under mass allocation	same direction, via precursor
Compliance pathway in Colombia	Fully covered: NTC 121, NSR-10 Title C	Covered: NTC 121 admits blended/added cement; performance specification required	Not directly covered: alternative-materials route (Law 400/1997) or project-specific approval
Rating under Table 1	Feasibility High/Env. Low/Readiness High	Feasibility Med–High/Env. Medium/Readiness Med–High	Feasibility Medium/Env. High/Readiness Low–Med

4.3.2. Boundary Conditions, Allocation Methods, and Regional Energy Mix

The environmental indicators synthesized in Tables 4 and 5 are conditioned by three methodological choices that deserve explicit treatment, since they can change not only the magnitude but occasionally the direction of reported advantages.

System boundaries. Most values in the reviewed corpus are cradle-to-gate, which favors materials whose burdens concentrate in production and penalizes none of the use-stage or end-of-life differences. This truncation systematically flatters low-durability options: a material with 40% lower embodied carbon but half the service life can be environmentally worse on a cradle-to-grave, per-year-of-service basis (see Section 5.5). Conversely, cradle-to-gate accounting omits credits that favor circular options, such as the recyclability of steel or the potential carbonation uptake of concrete during service and after crushing. Studies adopting cradle-to-grave boundaries for timber and bamboo also diverge on the treatment of biogenic carbon (0/0 versus $-1/+1$ conventions), which explains most of the spread between “low” and “net-negative” footprints reported for bio-based materials [56,58].

Allocation of by-product burdens. The advantage attributed to SCM-based concretes depends strongly on how the upstream burdens of fly ash and blast-furnace slag are allocated. Under the zero-burden (waste) convention, these materials carry only conditioning and transport emissions, and substitution benefits scale almost linearly with replacement level. Under economic allocation, part of the emissions of coal-fired electricity or primary steelmaking is assigned to the by-product, reducing the net benefit; under mass allocation the benefit can vanish entirely. The reviewed sources rarely state the convention used, which is a material source of non-comparability. In the Colombian context this question is not academic: national fly-ash availability is tied to a small number of coal plants, and slag to a limited steel sector, so both the physical supply and the defensible allocation basis are country-specific. The same logic applies in reverse to recycled aggregates, whose main burden is crushing and transport: comparative LCAs show that the advantage of recycled over natural aggregates holds only while the additional haul distance of the recycled material remains small—with break-even reported at additional road-haul distances on the order of 15 km, or equivalently whenever the recycled-aggregate haul exceeds that of the natural aggregate it replaces—beyond which transport emissions offset the benefit of avoided extraction [86].

Regional energy mix. Generic life-cycle databases embed electricity mixes (typically European or Chinese averages) that differ substantially from the Colombian grid, in which hydropower supplied 71.9% of National Interconnected System (SIN) generation in 2020 and 81.8% in 2021, with renewables reaching 83.4% of the total in the latter year [87]. The official SIN emission factor for GHG inventories and carbon footprinting was 0.220 t CO₂-eq/MWh in 2024 [88], a value elevated by the strong 2023–2024 El Niño episode, which temporarily increased thermal generation, and still well below world-average grid intensities; in wet years the factor is substantially lower, consistent with the hydropower shares above. This interannual, hydrology-driven variability is itself methodologically relevant: electricity-dependent LCA results for Colombia carry a temporal dimension that generic databases do not capture, and single-year coefficients should be interpreted accordingly. This has two consequences for the materials compared here. First, electricity-intensive routes are systematically less carbon-intensive when performed in Colombia than generic data suggest: scrap-based (EAF) steelmaking, aggregate crushing, and grinding of SCMs all benefit from the low-carbon grid, strengthening the case for recycled steel and recycled aggregates relative to Table 4 values. Second, process emissions that do not depend on electricity—above all limestone calcination in clinker production and fuel combustion in cement and brick kilns—are not reduced by the clean grid, so the relative penalty of

clinker-intensive and fired-clay products is amplified in the Colombian context. Interpreting imported LCA coefficients without this correction therefore biases comparisons against electricity-intensive circular routes and in favor of thermally driven conventional ones.

The direction of the reported advantages of eco-efficient materials is robust across these methodological choices for high-substitution cementitious routes and for bio-based materials, but the magnitude of the advantage—and, for marginal cases such as long-haul recycled aggregates or low substitution levels, its sign—depends on boundary, allocation, and grid assumptions. This is why the framework of Section 3.7 treats environmental indicators as directional evidence with declared context rather than as universal coefficients.

4.4. Colombia-Specific Readiness and Normative Alignment

The Colombian construction sector remains strongly anchored in conventional materials, supported by industrial capacity and mature standards for cement, steel, and masonry [89,90]. For eco-efficient alternatives, the documentary corpus shows growing research and pilot adoption—especially for SCM integration, recycled aggregates, and locally sourced solutions such as guadua and rammed earth—but scale-up remains limited by certification ecosystems, waste-management logistics, and uneven standardization. The normative landscape is evolving toward RCD valorization and sustainability requirements, but implementation performance (e.g., recycling rates and enforcement capacity) emerges as a central practical constraint.

The scale of the transition challenge can be quantified. National grey cement production reached 13.4 million tonnes in 2024 [91], implying—at the representative intensity of Table 4—on the order of 10–12 Mt CO₂-eq per year from cement alone, before considering steel and fired-clay products. On the waste side, Bogotá alone manages more than 13 million tonnes of construction and demolition waste per year, of which approximately 3.1 million tonnes (roughly 18–19%) were valorized in 2022 [92]; this is a substantial improvement over the ~2% national utilization rate estimated when the circular-economy policy baseline was set [93], yet it remains below the 25% incorporation target established for public and private works in the capital since 2017 [94], confirming the implementation gap discussed in Section 5. On the demand side, market signals are strong: Colombia has become the second-largest EDGE-certified market worldwide, exceeding 20 million m² of certified floor area by early 2025—65% of it certified within the preceding two years—with projected savings of about 190,000 t CO₂ per year, and approximately 73% of certified housing units corresponding to social housing (VIS) [95], with more than 650 LEED-registered projects (over 310 of them certified, totaling ≈7.0 million m² of certified floor area as of March 2025) complementing this ecosystem [96]. These figures indicate that certification-driven demand for low-impact materials is growing faster than the certified supply of such materials and the enforcement capacity of waste-valorization instruments, an asymmetry that defines the practical bottleneck for eco-efficient material adoption in Colombia.

The normative baseline is itself evolving: Resolution 0194 of 2025 of the Ministry of Housing replaced Resolution 0549 of 2015, tightening mandatory water- and energy-saving parameters for new buildings—including social housing—and recognizing certification schemes as verification mechanisms [97], which reinforces the trajectory toward performance-based sustainability requirements described in this review.

Key technical standards and policy instruments that enable or constrain adoption of SCMs, recycled aggregates, alternative binders, timber, and sustainability-oriented design/assessment practices in Colombia.

Table 7 outlines the main Colombian standards and policy instruments relevant to eco-efficient material adoption.

Table 7. Colombian regulatory and standards landscape relevant to eco-efficient material adoption.

Material or Scope	Regulation or Instrument	Primary Focus	Responsible Authority	Implementation Remarks
Portland cement	NTC 121 [98]; NTC 321 [99]	Quality control and performance requirements for hydraulic cements; allows supplementary cementitious materials	ICONTEC; Ministry of Housing	Transition toward performance-based specifications to enable emission reduction
Structural steel	NSR-10 (Title F); NTC 2289 [100]; NTC 5806 [101]	Structural safety and material quality for seismic-resistant steel structures	Ministry of Housing; ICONTEC	Encourages recycled steel use and energy-efficient production routes
Ceramic brick	NTC 4017 [102]	Compressive strength testing and dimensional control of clay masonry units	ICONTEC	Permits incorporation of industrial by-products without compromising quality
Geopolymers and alkali-activated materials	NTC 4026 [103]; NSR-10	Classification and structural validation of alternative cementitious materials	ICONTEC; Ministry of Housing	Meets seismic and mechanical requirements for sustainable construction
Recycled aggregates and construction and demolition waste (CDW)	INV E-218 [104]; INV E-224 [105]; National CDW Policy [5]	Physical and mechanical testing; minimum 25% CDW utilization target	INVIAS; Ministry of Environment	Current recycling rates (~17%) remain below regulatory targets
Recycled asphalt and road materials	Applicable NTC and INV standards	Reuse of reclaimed asphalt pavement and recycled aggregates in road infrastructure	INVIAS; ICONTEC	Ensures performance through standardized testing protocols
Structural timber	NSR-10 (Title G) [80]; NTC 1500; NTC 5525	Design and quality control of timber structural elements	ICONTEC; Ministry of Housing	Promotes responsible use and sustainable forest management
Sustainable construction and LCA	Resolution 0194 (2025), replacing Resolution 0549 (2015); National Development Plan 2022–2026	Integration of sustainability criteria and life cycle assessment in buildings	Ministry of Housing; Ministry of Environment	Resolution 0194/2025 tightens mandatory savings parameters and homologates certification schemes (e.g., EDGE) as verification mechanisms

Synthesizing the technical, environmental, and normative evidence, the material families reviewed can be grouped into three applicability classes for current Colombian practice. Class A—structurally applicable now under existing standards: conventional concrete, structural steel, engineered timber under NSR-10 Title G, and SCM-based concretes within the substitution levels admitted by NTC 121 performance specifications; for these families, adoption is a specification and procurement decision, not a regulatory one. Class B—applicable in defined niches, with engineering governance: recycled-aggregate concretes (non-structural and limited structural uses with quality control over source streams and absorption), guadua structural systems for low- and mid-rise buildings under NSR-10 Title G-12 with mandatory preservation and detailing, and stabilized rammed earth for low-rise walls in regions with supporting practice; these families are technically viable today but their acceptance is conditional and project-specific. Class C—requiring standardization, certification, or durability track record before structural adoption: geopolymers and alkali-activated concretes (no prescriptive Colombian standard; alternative-materials route under Law 400 of 1997), recycled-content masonry seeking structural classification, bio-based composites beyond insulation functions, and self-healing or nano-modified concretes (pending standardized test methods and harmonized service-life evidence [60]). This classification is deliberately time-stamped: several Class C families have active standardization processes internationally, and their reclassification into Class B is plausible within the decade if durability datasets and certification ecosystems mature.

5. Discussion

The synthesized evidence confirms that traditional construction materials—Portland cement, concrete, structural steel, ceramic bricks, and timber—remain dominant due to their availability, standardized performance, and regulatory acceptance. How-

ever, their extensive use is strongly associated with the highest environmental burdens in the sector, particularly CO₂ emissions, energy consumption, and depletion of non-renewable resources.

Conversely, the reviewed literature shows a consistent shift toward eco-efficient materials based on industrial residues, recycled components, and renewable resources. These alternatives achieve substantial reductions in embodied emissions and, in many cases, comparable or improved durability when properly designed. Although their adoption in Colombia remains uneven, the trend reflects a broader transition from performance-only material selection toward sustainability-driven decision-making.

5.1. Implications for Sustainable Civil Engineering

The results indicate that civil engineering is undergoing a structural adaptation to sustainability constraints. Conventional materials retain dominance due to proven mechanical reliability, yet their environmental impact necessitates immediate mitigation strategies. Eco-efficient materials offer significant environmental advantages but require stronger technical validation and regulatory integration to gain widespread acceptance.

Technically, the most effective strategies include optimized mix designs, the use of supplementary cementitious materials, and the valorization of industrial residues. Advances in computational modeling, life cycle assessment (LCA), and performance-based testing increasingly support the validation of these materials under realistic service conditions.

Material selection in Colombia must also account for regional climatic and geotechnical variability. Locally adapted solutions that exploit available resources while reducing dependence on energy-intensive inputs are essential. Embedding sustainability as a design criterion further implies changes in professional training and public procurement, including environmental performance requirements in project evaluation.

5.2. Colombian Context: Trends, Limitations, and Potential

Colombia shows a gradual transition toward more sustainable construction practices, driven by environmental regulation and public policy. Nevertheless, implementation remains limited by economic constraints, insufficient recycling infrastructure, and uneven technical capacity. Current CDW recycling rates remain well below policy targets.

Despite these limitations, notable progress is evident in regions such as the Coffee Belt and Santander, where academic–industry collaborations have enabled housing and infrastructure prototypes using guadua, recycled masonry units, and stabilized soils. These initiatives exhibit growing alignment between sustainability objectives, local resource use, and construction practice.

The main challenge lies in strengthening links between research, industry, and policy to translate innovation into large-scale application. Technical standards, sustainability certification schemes, and green financing mechanisms are critical enablers of this transition.

5.3. Transition Toward Eco-Efficient Materials: Comparative Insights

The review shows sustained growth in research and pilot applications of eco-efficient materials in Colombian construction between 2010 and 2025. Clinker-reduced concretes, lime- and ash-stabilized soils, and *Guadua angustifolia* structural systems emerge as viable alternatives to conventional materials.

Studies show that pozzolanic concretes can reach compressive strengths comparable to conventional mixes while reducing CO₂ emissions by up to 40%. Recycled aggregates preserve acceptable mechanical performance when replacement ratios are controlled, while stabilized soils significantly improve bearing capacity for low-volume road infrastructure. Guadua-based systems combine competitive mechanical properties with rapid renewability and low embodied carbon.

Overall, eco-efficient materials provide a more favorable balance between structural performance and environmental impact, supporting a shift toward hybrid and context-specific construction solutions. To synthesize the technical, environmental, and regulatory evidence discussed in the preceding sections, a comparative matrix is presented in Table 8. This matrix contrasts traditional construction materials with eco-efficient alternatives across key criteria relevant to material selection under sustainability constraints. The comparison highlights trade-offs in mechanical performance, environmental impact, regulatory readiness, and practical implementation, thereby illustrating the potential of eco-efficient materials as viable and progressively adopted alternatives within the Colombian construction sector.

Table 8. Comparative assessment of traditional and eco-efficient construction materials.

Criterion	Traditional Materials (Portland Cement, Structural Steel, Ceramic Brick, Timber)	Eco-Efficient Materials (Geopolymers, Blended Concretes, Recycled Aggregates, Eco-Bricks, Guadua Bamboo, Rammed Earth, Biocomposites)
Origin and composition	Predominantly virgin raw materials: limestone, clay, iron ore, natural timber	Industrial by-products, agricultural residues, recycled materials, and renewable resources (fly ash, slag, rice husk ash, sugarcane bagasse, guadua)
Manufacturing process	Highly energy-intensive (calcination, smelting, sintering); fossil fuel dependent	Lower energy demand; alkaline activation, cold curing, or recycling-based processes
Mechanical performance	Proven high strength: concrete (25–70 MPa), steel (400–600 MPa), brick (7–20 MPa), timber (20–100 MPa)	Competitive but application-dependent: geopolymers and eco-concretes (49–172 MPa), eco-bricks (3–43 MPa), guadua (40–60 MPa), rammed earth (≤ 5 MPa)
Durability	High, but strongly dependent on maintenance and exposure; steel and timber require protection	Good durability under controlled moisture and compaction; geopolymers show high chemical and thermal resistance
Weight and density	Generally high (concrete and brick: 1600–2400 kg/m ³); timber lighter but variable	Lower weight systems; eco-blocks, guadua, and biocomposites reduce structural loads
Environmental impact (CO ₂ and energy)	High: cement (~0.9 t CO ₂ /t), steel (~1.8 t CO ₂ /t), brick (200–400 kg CO ₂ /t)	40–85% emission reduction; some materials store biogenic carbon
Natural resource consumption	High reliance on mining and forestry extraction	Reduced use of virgin resources through recycling and renewable inputs
Recyclability and reuse	Limited (except steel); cement and bricks have low recycling rates	High; recycled aggregates, eco-blocks, and bio-based materials reintegrate into circular loops
Health and air quality impacts	Significant particulate matter, NO _x , and SO ₂ emissions during production	Lower emissions; some natural materials improve indoor air quality
Colombian regulatory status	Fully regulated by consolidated standards (NTC 121, NTC 321, NTC 4017, NSR-10)	Emerging and partial regulation (NTC 4026, NTC 6421, Resolution 0194/2025, CDW Policy 2021 [5])
Structural applicability	Fully structural; basis of conventional design practice	Transitional: eco-concretes and geopolymers structurally viable; guadua and rammed earth mainly for low-rise buildings
Costs and availability	High national availability; mature industrial processes; stable costs	Variable costs; potential long-term savings via reduced maintenance and energy demand
Innovation level	Incremental improvements in efficiency and quality	High innovation: 3D printing, nano-modification, self-healing systems, biocomposites
Colombian context	Extensive industrial infrastructure; strong technical dependence	Growing adoption in La Guajira, Cesar, Eje Cafetero, and Santander
Alignment with circular economy and SDGs	Limited; predominantly linear production models	Strong alignment; promotes waste valorization, resource efficiency, and decarbonization

5.4. Technical and Regulatory Barriers to Adoption in Colombia

Despite their potential, eco-efficient materials face significant adoption barriers. Limited technical knowledge among practitioners reduces confidence in alternative materials, while outdated industrial infrastructure constrains process innovation and energy efficiency.

Regulatory frameworks prioritize structural safety, with limited integration of environmental indicators such as embodied carbon. Although recent policies address recycled

materials and CDW management, enforcement remains inconsistent and economic incentives are scarce. The absence of standardized testing protocols for emerging materials further delays regulatory acceptance.

Addressing these challenges requires coordinated action across education, standardization, financial incentives, and institutional governance. Strengthening professional training, developing certification schemes, enabling green financing, and improving inter-institutional coordination are essential to accelerate Colombia's transition toward a low-carbon, resource-efficient construction sector.

5.5. Durability, Service Life, and End-of-Life as Environmental Variables

The comparative results of Section 4 are expressed per unit of material, which is the dominant reporting convention in the reviewed corpus. However, when materials differ in expected service life, the environmentally meaningful metric is impact per year of delivered function: a material with 40% lower embodied carbon but half the service life of its conventional equivalent implies more frequent replacement and can accumulate a larger burden over the building life cycle once manufacturing, transport, and installation of replacements are included. Durability is therefore not a purely technical attribute but a first-order environmental variable, and this coupling is strongest precisely for the unconventional materials that show the largest cradle-to-gate advantages.

Tropical Andean and Caribbean service conditions accentuate this coupling. For *Guadua angustifolia* and timber, the governing degradation mechanisms are biological (fungal decay, subterranean and drywood termites, powder-post beetles), and untreated elements exposed to moisture can lose structural capacity within a few years, whereas properly preserved and detailed elements reach multi-decade service lives [58,62,63]. The preservation treatments themselves (e.g., boron-based impregnation) and the constructive detailing required to keep members dry (roof overhangs, elevated foundations, ventilation) carry modest environmental costs that should be charged to the bio-based option in a fair comparison, but they are decisive for its effective service life. For rammed earth, the dominant mechanisms are surface erosion under driving rain and moisture-induced strength loss; stabilization (lime or cement) and protective design mitigate them at the cost of part of the material's carbon advantage, a cement-stabilized rammed earth wall can approach the footprint of conventional masonry if stabilizer content is high [57]. For recycled-aggregate and high-substitution SCM concretes, the durability questions are chloride ingress in coastal environments, carbonation-induced depassivation, and sulfate exposure; the reviewed evidence indicates that these risks are controllable through permeability reduction and adequate curing [50–54], but they impose a quality-control regime whose institutional feasibility in Colombia is uneven. Fire performance adds a further constraint for bio-based insulation and composites, which typically require protective layers or treatments to meet building fire-safety expectations [56,61]; these protections again add embodied impacts that are rarely included in the primary studies.

End-of-life pathways complete the picture. Steel retains high value through established recycling chains, and its end-of-life credit is the main reason its life-cycle profile improves markedly under cradle-to-grave accounting [8,66]. Concrete and masonry are downcycled at best—crushed into aggregates for bases and sub-bases—which avoids disposal and virgin extraction but does not recover the embodied burden of clinker; partial recarbonation of crushed concrete recovers a modest fraction of calcination emissions. Bio-based materials present the widest spread of outcomes: reuse or cascading preserves stored biogenic carbon, whereas landfilling with anaerobic decay can convert it into methane, turning a carbon-storing material into a net emitter under some accounting conventions [56]. Geopolymers and alkali-activated materials currently lack established end-of-life valorization routes,

and their long-term field durability record remains short [30], which is one reason their evidence-quality rating in Table 5 is Medium despite strong laboratory performance.

Two implications follow for the framework. First, cradle-to-gate advantages of low-durability options should be read as upper bounds; a service-life-normalized comparison (impact per m² of function per year) is the appropriate basis for policy instruments such as public procurement criteria. Second, durability-enhancing strategies—preservation of bio-based materials, stabilization of earth systems, permeability control in eco-efficient concretes, and self-healing technologies [59,60]—should be evaluated as environmental investments whose payback is measured in avoided replacement cycles, not as cost over-heads. Future work should couple the present framework with probabilistic service-life models and Colombian exposure data to make this normalization explicit.

6. Conclusions

This study highlights the inherent trade-off between structural performance and environmental impact in material selection for civil construction in Colombia. Conventional materials—Portland cement, structural steel, ceramic bricks, and timber—remain indispensable due to their mechanical reliability and regulatory maturity, yet they account for the highest embodied energy demand and CO₂ emissions within the sector, reinforcing the need for a structural shift toward sustainability-oriented construction practices. Beyond summarizing the available literature, this study contributes an integrated comparative framework that links technical feasibility, environmental performance, and regulatory readiness, enabling a decision-oriented interpretation of material selection pathways for the Colombian construction sector.

Eco-efficient materials, including mineral-admixed concretes, geopolymers, *Guadua angustifolia*, and rammed earth, show clear potential to decouple structural performance from environmental burden. Reported emission reductions of up to 85%, combined with improved resource efficiency and circular material flows, support their potential viability as low-carbon alternatives without compromising functional requirements.

Although Colombia has established regulatory instruments to promote sustainable construction and demolition waste (CDW) valorization, their implementation remains limited, with recycling rates below 20%. This persistent gap between policy intent and construction practice highlights the need for stronger institutional coordination, technical standardization, and performance-based regulations that integrate environmental indicators alongside structural safety requirements.

Local pilot applications—such as slag-based concretes, eco-bricks, and guadua-based structural systems—illustrate the role of academic research and regional innovation in advancing material sustainability. However, large-scale adoption continues to be constrained by cost uncertainty, limited certification frameworks, and insufficient economic incentives, underscoring the importance of aligning innovation with market and regulatory mechanisms. Beyond synthesizing the available literature, the proposed framework provides a practical decision-support structure for evaluating construction materials under technical, environmental, and regulatory constraints. By integrating these dimensions within a common comparative framework, the study supports more informed material-selection strategies for sustainable construction in Colombia.

Because this study follows a structured narrative review design, its findings should be interpreted as an integrative and decision-oriented synthesis rather than as quantitative estimates of material performance or environmental impact. PRISMA-based screening, formal risk-of-bias assessment, and statistical aggregation of effect sizes were not performed; therefore, the conclusions reflect patterns identified across heterogeneous scientific, technical, and regulatory sources rather than pooled effect measures.

Future research should therefore expand environmental assessment boundaries beyond cradle-to-gate approaches to include full life-cycle perspectives, accounting for end-of-life scenarios, reuse potential, and long-term durability. In parallel, integrating economic dimensions such as life-cycle costing and cost–benefit analysis is essential to complement technical and environmental evaluations and support decision-making in public procurement and infrastructure planning. Extending this integrated assessment framework to other construction-related sectors, including transportation infrastructure and prefabricated systems, would further enhance its applicability and contribute to the broader transition toward low-carbon, resource-efficient construction.

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