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Systematic Review

Materials Pathways for Low-Carbon Construction: A Systematic Review of Bio-Based, Recycled, and Alternative Cementitious Systems

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Abstract

The construction sector is responsible for significant global energy consumption and CO_2 emissions, largely driven by carbon-intensive materials such as ordinary Portland cement and steel. In response to increasing decarbonization and circular economy demands, several strategically relevant categories of sustainable construction materials have been developed, particularly natural and bio-based systems, recycled and waste-derived materials, low-carbon cementitious binders, and emerging multifunctional composites. However, research remains fragmented across material classes and performance metrics. This systematic review evaluates advances published between 2018 and 2026 following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 methodology. Peer-reviewed studies were systematically identified and analyzed to compare mechanical performance, durability, embodied carbon reduction, and life-cycle environmental impacts across these selected material pathways. The results indicate substantial decarbonization potential. Low-carbon cementitious materials report CO_2 reductions of approximately 10–75% relative to conventional systems, while engineered timber and bamboo demonstrate 28–70% lower carbon footprints due to reduced embodied energy and biogenic carbon storage. Recycled aggregates and industrial by-products enhance circularity but remain sensitive to transport distance and processing intensity. Trade-offs between mechanical capacity and environmental performance are evident in lightweight and bio-based systems. Overall, sustainability gains are maximized through integrated hybrid construction strategies rather than isolated material substitution. This review provides a comparative evidence-based synthesis and identifies key research gaps and implementation challenges for accelerating low-carbon construction.

Keywords: sustainable construction materials; low-carbon cementitious materials; bio-based and recycled materials; life cycle assessment; decarbonization

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1. Introduction

The construction sector plays a fundamental role in global economic development and urbanization; however, it remains one of the most resource-intensive and carbon-emitting industries worldwide [1]. The built environment accounts for approximately

34% of global final energy consumption and nearly 37% of energy-related CO_2 emissions, largely driven by the production of ordinary Portland cement (OPC), steel manufacturing, energy-intensive processing routes, and extensive extraction of virgin raw materials [2]. In parallel, growing volumes of construction and demolition waste (CDW) intensify pressure on landfills, ecosystems, and material supply chains. These environmental burdens are increasingly incompatible with international climate mitigation commitments, circular economy strategies, and the United Nations Sustainable Development Goals (SDGs) [3].

The sector therefore faces a systemic challenge: achieving substantial reductions in embodied carbon and resource depletion while maintaining structural reliability, durability, functional performance, and economic feasibility [4]. Conventional materials—particularly OPC-based concrete and steel—remain dominant due to established supply chains, standardized regulations, and proven mechanical performance. However, their high carbon intensity limits the effectiveness of incremental efficiency improvements [5]. Meeting decarbonization targets requires structural transformation of material systems rather than isolated optimization of conventional practices [6].

In response, multiple sustainable material pathways have emerged during the past decade. Natural and bio-based materials—such as engineered timber, bamboo, hemp-based composites, and agro-residue-derived systems—offer renewable sourcing and carbon sequestration potential [7]. Recycled and waste-derived materials—including recycled concrete aggregates, industrial by-products, and polymer-based composites—promote circular resource flows and landfill diversion [8]. Alternative and low-carbon cementitious materials (LCCMs), such as supplementary cementitious materials (SCMs), alkali-activated materials (AAMs), and limestone calcined clay cement (LC3), aim to reduce clinker content and associated process emissions [9]. Additionally, innovative smart systems—including self-healing concrete, phase change materials (PCMs), and additive manufacturing-enabled composites—expand the functional design space by integrating durability enhancement and energy efficiency into material performance [10].

Despite rapid growth in research output, the existing literature remains highly fragmented across material classes, performance criteria, and assessment methodologies [11,12].

Some previous studies evaluate specific sustainability dimensions separately—including mechanical performance, thermal behavior, durability, and environmental indicators, particularly embodied carbon—without integrating these criteria together with economic feasibility and implementation barriers within a comparative assessment framework [13].

Furthermore, life cycle assessment (LCA) results often depend on region-specific assumptions, system boundaries, allocation methods, and end-of-life scenarios, limiting cross-study comparability. While numerous narrative and thematic reviews address specific materials (e.g., geopolymers, recycled aggregates, bio-composites), comprehensive systematic comparisons across multiple sustainable material classes remain limited [14].

Several influential reviews have significantly advanced understanding of individual sustainable material pathways, including geopolymers, recycled aggregates, timber systems, and bio-based composites. However, these studies are typically organized around single material families or narrowly defined objectives, which limits direct comparison across competing alternatives under common decision criteria [7,9,13,14]. In practice, mechanical performance, durability, embodied carbon, scalability, cost, and regulatory readiness are often assessed separately, generating fragmented evidence for stakeholders seeking integrated material selection strategies.

Accordingly, the present review seeks to move beyond descriptive cataloguing by identifying cross-cutting trade-offs, recurring implementation bottlenecks, and evidence gaps shared across major material pathways. The added scientific contribution lies not only in synthesis breadth, but in the comparative integration of heterogeneous material classes within a unified sustainability-oriented evaluation framework.

It should be noted that this review does not aim to exhaustively cover every construction material category. Instead, it focuses on selected material pathways currently recognized as strategically relevant for construction decarbonization and circularity transitions, particularly bio-based materials, recycled systems, low-carbon cementitious binders, and emerging multifunctional technologies. Other important sectors such as glass, ceramics, gypsum-based systems, and metals deserve dedicated reviews due to their distinct manufacturing processes, performance metrics, and environmental profiles.

This fragmentation highlights the need for a transparent, reproducible, and multi-dimensional synthesis of recent advances. Accordingly, this study conducts a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 [15] protocol to identify, evaluate, and synthesize peer-reviewed research published between 2018 and 2025. This period captures accelerated innovation in low-carbon binders, circular material strategies, bio-based systems, and performance-based sustainability assessment frameworks.

The present review addresses the following research questions:

- How can selected sustainable construction materials be systematically classified according to composition, processing route, and application?
- How do natural-based, recycled, and low-carbon cementitious materials compare in terms of mechanical performance, durability, and functional properties?
- What ranges of embodied carbon reduction are reported across different material classes, and how robust are these findings under life cycle assessment frameworks?
- What economic, regulatory, and technological barriers constrain large-scale implementation?
- What emerging trends and innovation pathways are shaping the transition toward circular and low-carbon construction systems?

The central hypothesis of this review is that sustainable material transition is not driven by isolated material substitution, but by integrated hybrid systems that combine structural optimization, durability enhancement, circular resource flows, and life cycle-oriented assessment. Therefore, the objective of this study is to provide a comprehensive and methodologically rigorous synthesis that integrates technical performance indicators with environmental, economic, and implementation dimensions. By linking material innovation to systemic adoption challenges, this review aims to support evidence-based material selection, inform policy development, and identify priority research directions for accelerating decarbonization of the built environment.

This paper is structured as follows. Section 1 provides the Introduction, presenting the environmental context of the construction sector, the need for sustainable material innovation, the research gaps identified in the existing literature, and the objectives and scope of this systematic review. Section 2 presents the Materials and Methods, describing the PRISMA 2020 protocol [15], Scopus search strategy, and screening process for studies published between 2018 and 2025, together with the bibliometric analysis and comparative analytical framework adopted in this review. Section 3 reports the Results, synthesizing findings across natural-based materials, recycled systems, alternative low-carbon cementitious binders, and innovative sustainable technologies, complemented by sustainability performance assessment approaches. Section 4 provides a Discussion, critically comparing material categories, evaluating trade-offs between mechanical performance and environmental impact, analyzing barriers to adoption, and identifying research gaps and strategic priorities. Finally, Section 5 presents the Conclusions, summarizing the principal insights

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and outlining future pathways for advancing durable, resource-efficient, and low-carbon construction materials.

2. Materials and Methods

2.1. Systematic Review Sequence

This systematic review was conducted following the guidelines established by the PRISMA Statement 2020 [15], which provides a structured methodological framework that ensures transparency, reproducibility, and scientific rigor throughout the identification, screening, eligibility, and inclusion stages of relevant studies. The adoption of this protocol made it possible to minimize bias in the selection of the literature, as well as to ensure methodological consistency and traceability of the review process. This approach is widely recognized as the international standard for systematic reviews in areas related to materials science, engineering, and sustainability, enabling the logical and systematic organization of existing knowledge.

Likewise, the review protocol was retrospectively registered in the Open Science Framework (OSF): https://doi.org/10.17605/OSF.IO/HA26G. The completed PRISMA 2020 checklist is provided as Supplementary Material to ensure full compliance with the reporting standards.

2.2. Database and Search Strategy

The bibliographic search was carried out using the Scopus database, selected due to its extensive coverage of the peer-reviewed scientific literature in key areas such as engineering, materials science, energy, and environmental sciences. This database is recognized for its high quality, reliability, and multidisciplinary scope, making it an appropriate source for systematic reviews related to sustainable construction materials.

Scopus was selected as the primary database because it offers broad multidisciplinary coverage, and strong indexing of engineering, materials science, environmental, and construction-related journals, as well as compatible metadata export for bibliometric analysis and screening workflows. Although additional databases such as Web of Science may retrieve complementary records, Scopus was considered sufficiently comprehensive for the comparative objectives of this review.

The search was conducted in January 2026, with the aim of identifying studies related to sustainable construction materials, low-carbon cementitious materials, bio-based materials, recycled materials, and their environmental impact in terms of carbon footprint and CO_2 emissions.

The final search query used was as follows: TITLE-ABS-KEY ((“sustainable construction material*” OR “low-carbon cementitious material*” OR “bio-based material*” OR “recycled construction material*”) AND (“carbon footprint” OR “CO_2 emission*” OR “life cycle assessment”)) AND PUBYEAR > 2017 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA, “ENGI”) OR LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “MATE”) OR LIMIT-TO (SUBJAREA, “ENER”) OR LIMIT-TO (SUBJAREA, “CENG”) OR LIMIT-TO (SUBJAREA, “CHEM”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (LANGUAGE, “English”)).

The query combined material-related descriptors (sustainable construction material, low-carbon cementitious material, bio-based material, recycled construction material) with environmental descriptors (carbon footprint, CO_2 emission), together with publication year, subject-area, document-type, and language filters available in the Scopus advanced search environment.

A temporal filter was applied, restricting publications to the period between 2018 and 2026, in order to ensure that the analysis reflects the most recent scientific advances in the development of sustainable construction materials and decarbonization strategies. Additionally, the search was limited to research articles and review articles published in English, ensuring scientific quality and accessibility of the content.

Likewise, the search strategy was intentionally designed to support a comparative multi-material systematic review rather than an exhaustive census of any single material subfield. Therefore, the retrieved records should be interpreted as studies matching the predefined interdisciplinary scope of this review.

2.3. Inclusion and Exclusion Criteria

In order to ensure the scientific quality, thematic coherence, and relevance of the selected studies, explicit inclusion and exclusion criteria were established, aligned with the objectives of this systematic review. The definition of these criteria allowed the structuring of a transparent, reproducible, and unbiased selection process, ensuring that the selected studies contributed significantly to the analysis of environmental performance and sustainability of construction materials.

2.3.1. Inclusion Criteria

Studies were included when they met the following conditions:

Document type: Research articles and review papers published in peer-reviewed scientific journals were included, ensuring the methodological and scientific quality of the sources.

Publication period: Studies published between 2018 and 2026 were considered, in order to analyze current trends and recent advances in sustainable construction materials.

Language: Publications written in English were included, due to their wide international dissemination and scientific accessibility.

Subject area: Studies belonging to the following areas were included:

Engineering, Environmental Science, Materials Science, Energy, Chemical Engineering, Chemistry, and Computer Science.

This filtering ensured the technical and scientific relevance of the selected studies.

Thematic focus: Studies had to address at least one of the following topics:

Sustainable construction materials, low-carbon cementitious materials, bio-based construction materials, recycled construction materials, carbon footprint assessment, or CO_2 emissions associated with construction materials.

Environmental relevance: Studies focused on the following aspects were included:

Environmental performance assessment, decarbonization strategies, sustainability evaluation, and carbon emission reduction.

2.3.2. Exclusion Criteria

Studies were excluded when they met one or more of the following conditions:

Conference papers, book chapters, editorials, technical notes, and short communications were excluded.

Studies not directly related to construction materials were excluded.

Exclusively mechanical or structural focus: Studies focused only on mechanical properties without considering environmental or sustainability aspects were excluded.

Unrelated areas: Studies focused on the following areas were excluded:

Biomedical applications, electronic materials, polymeric materials without application in construction, and pharmaceutical applications.

Duplicates: All duplicate records identified in the database were removed.

Full-text accessibility: Studies without accessible full text were excluded, as they did not allow adequate evaluation.

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It is acknowledged that database coverage, keyword selection, language restrictions, and eligibility thresholds may influence the final study pool. However, these criteria were predefined and consistently applied to maximize transparency, thematic relevance, and reproducibility.

Figure 1 presents the flow diagram corresponding to the guidelines of the PRISMA 2020 Statement [15].

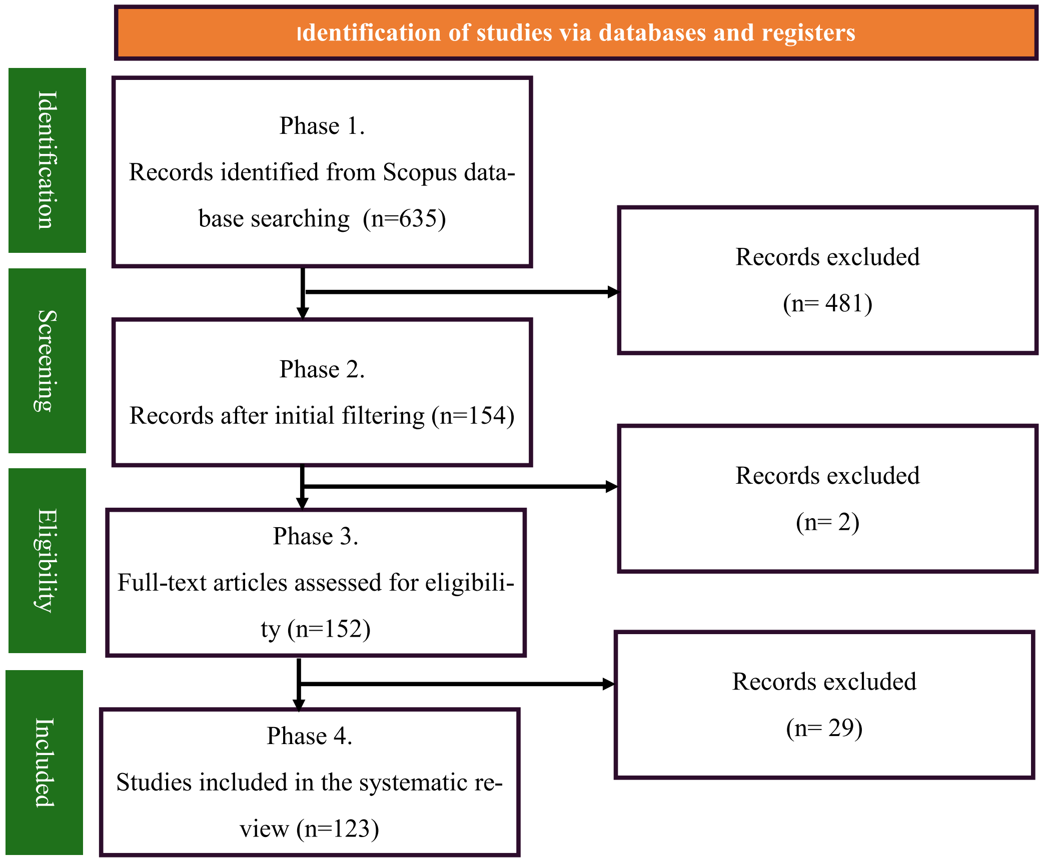

Figure 1. PRISMA flow diagram illustrating the study identification, screening, eligibility, and inclusion process for publications related to sustainable construction materials published between 2018 and 2026. Records shown correspond to studies retrieved within the predefined search scope of this systematic review and should not be interpreted as the total publication volume of the broader field.

In Phase 1, the initial search conducted in the Scopus database retrieved a total of 635 records, reflecting the growing scientific interest in the development and evaluation of sustainable construction materials, as well as in the reduction of carbon emissions associated with the construction sector. However, after applying the preliminary filtering criteria related to thematic scope, document type, language, and publication period, 481 records were excluded, mainly due to their lack of direct relevance to the environmental focus, their association with non-relevant subject areas, or their ineligible document type.

Subsequently, in Phase 2, 154 records were obtained and subjected to a more detailed review. At this stage, 2 additional studies were excluded, due to inconsistencies with the objectives of the review or limited thematic relevance.

In Phase 3, 152 full-text articles were assessed, representing a critical stage in the selection process, as it allowed precise verification of compliance with the established inclusion criteria. During this phase, 28 studies were excluded, mainly because they did not directly address environmental performance, carbon footprint, or decarbonization strategies in construction materials, or because they focused exclusively on mechanical properties without considering environmental impact.

Record screening was conducted through sequential title/abstract review followed by full-text eligibility assessment using the predefined criteria. Borderline cases were re-evaluated iteratively to improve consistency of inclusion decisions.

Finally, in Phase 4, 125 studies were selected, which fully met all the methodological, thematic, and scientific quality criteria defined in this systematic review. This final set of articles constitutes the basis for the qualitative and bibliometric analysis carried out in the present study.

Overall, the selection process demonstrates a rigorous and structured procedure, in which approximately 19.5% of the initially identified records were considered eligible and included in the final review. This progressive refinement ensured that the analyzed body of literature is highly relevant, up-to-date, and aligned with the objective of evaluating advances, environmental performance, and future perspectives of sustainable construction materials.

2.4. Conceptual Structure of the Research Field

Figure 2 shows the bibliometric network of keyword co-occurrence associated with the field of sustainable construction materials, which allows the identification of the conceptual structure, the main thematic cores, and the interrelationships among different research lines. The size of the nodes reflects the frequency of occurrence of each term, while the links indicate the degree of relationship between concepts, and the colors represent differentiated thematic clusters.

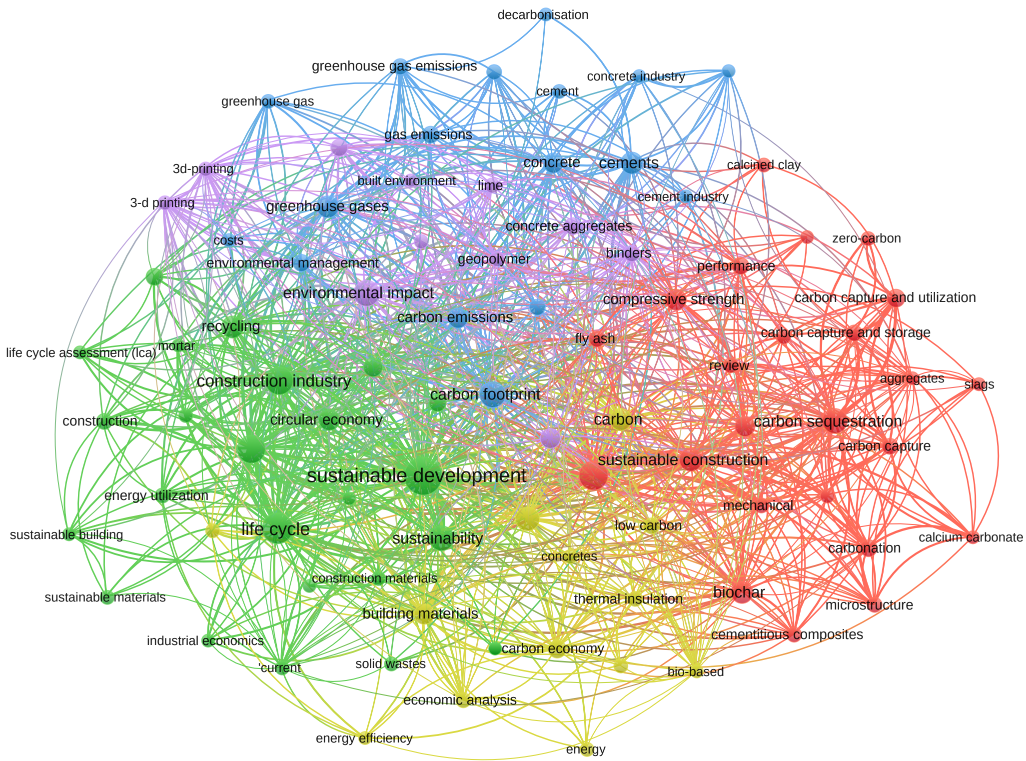

Figure 2. Bibliometric network of keyword co-occurrence in sustainable construction materials research generated from the Scopus database.

In general, the term "sustainable development" appears as one of the largest central nodes, highlighting that sustainable development represents the integrative axis of the research field. Its close relationship with terms such as "life cycle assessment," "sustainability," "construction industry," and "building materials" indicates that life cycle-based environmental assessment has been consolidated as one of the main methodological tools to quantify the environmental impact of construction materials. This cluster, represented in green, reflects a strong orientation toward comprehensive environmental evaluation and systemic analysis of sustainable performance.

On the other hand, the cluster represented in blue is dominated by terms such as “carbon footprint,” “carbon emissions,” “cement,” “concrete,” and “greenhouse gas emissions,” revealing that research in this field is strongly focused on the quantification and mitigation of carbon emissions, particularly in cementitious materials. The strong connectivity among these terms confirms that cement and concrete remain the primary focus of research due to their significant contribution to global CO_2 emissions, which has driven the development of more sustainable alternatives.

In the same way, the cluster identified in red groups several co-occurring keywords associated with emerging low-carbon research directions, including “carbon sequestration,” “carbon capture,” “biochar,” “carbonation,” and “cementitious composites.” These terms should be understood as distinct but related topics within the retrieved literature rather than equivalent technologies. Specifically, they encompass carbon management strategies, bio-based or waste-derived additives, CO_2 mineralization or curing processes, and advanced cementitious material development. The presence of the term “biochar” also indicates growing interest in carbon-storing bio-based additives within construction materials research.

Additionally, the cluster represented in yellow shows a relevant connection among terms such as “durability,” “thermal insulation,” “low carbon,” and “economic analysis,” suggesting that sustainability is not only evaluated from an environmental perspective but also considering technical and economic aspects. This reflects the evolution of the field toward multidimensional approaches integrating environmental performance, durability, and economic feasibility.

Overall, the network structure reveals that the field of sustainable construction materials is organized around three fundamental pillars: environmental assessment through life cycle methodologies, carbon emission reduction in cementitious materials, and the development of new solutions based on alternative materials and carbon capture technologies. The high density of connections among clusters indicates that these areas do not develop independently but rather form part of a highly interdisciplinary research framework.

Finally, the prominence of terms related to carbon footprint, emissions, and carbon capture confirms that decarbonization constitutes the main driving force of current research in sustainable construction materials. This trend reflects the increasing scientific, industrial, and regulatory pressure to develop materials with lower environmental impact, positioning this field as one of the key strategic areas for climate change mitigation within the construction sector.

2.5. Comparative Synthesis Framework for Sustainability Assessment

Given the heterogeneity of sustainable construction materials reported across the reviewed literature—including low-carbon cementitious materials (LCCMs), recycled aggregates, bio-based systems, engineered timber, and smart multifunctional materials—a unified comparative synthesis framework was adopted to enable consistent interpretation of mechanical performance, durability, and environmental impact indicators.

Because the reviewed studies differ substantially in specimen geometry, curing conditions, functional units, reporting formats, environmental boundaries, and performance metrics, a formal pooled meta-analysis or regression-based normalization was outside the scope of the present review. Accordingly, the framework is intended as an interpretative tool to support structured comparison of recurring patterns and trade-offs across heterogeneous datasets.

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Rather than proposing new predictive models, this review employs well-established analytical relationships from cementitious materials science, structural mechanics, and life cycle assessment (LCA) to normalize and interpret heterogeneous experimental data. These formulations provide a coherent basis for discussing trade-offs among conventional OPC-based systems and emerging sustainable alternatives.

2.5.1. Normalization of Compressive Strength

To enable comparison of structural performance across studies employing different specimen geometries and testing standards [16], compressive strength values are interpreted using the standard stress relationship:

$$f_c = \frac{F_{\max}}{A} \tag{1}$$

where f_c is the compressive strength (MPa), $F_{\max}$ is the maximum applied load at failure (N), and A is the loaded cross-sectional area (mm^2). When available, strength data reported in accordance with recognized standards (e.g., ASTM C39, EN 12390) [17] are prioritized to reduce methodological variability.

2.5.2. Strength–Porosity Relationship

Porosity is a primary microstructural parameter governing mechanical resistance and durability in cementitious and recycled systems [18]. The reduction in compressive strength with increasing porosity can be described using an exponential relationship of the Ryshkewitch–Duckworth type:

$$f_c = f_{c0} e^{-bP} \tag{2}$$

where f_c is the effective compressive strength, f_{c0} is the strength of the fully dense material, P is total porosity (–), and b is a material-dependent constant related to pore morphology and connectivity.

Although specific parameters vary across material systems, this relationship provides a robust interpretative basis for discussing performance differences between conventional concrete, SCM-based systems, recycled aggregate concretes, and bio-based composites.

2.5.3. Elastic Modulus and Structural Efficiency

The effective elastic modulus of porous cementitious systems may be approximated using [19]:

$$E = E_0 (1 - P)^n \tag{3}$$

where E is the effective elastic modulus, E_0 is the modulus of the dense matrix, P is total porosity, and n is an exponent dependent on pore geometry and distribution.

This formulation supports interpretation of stiffness reductions observed in lightweight concretes, recycled systems, and bio-based composites, highlighting the trade-off between density reduction and structural rigidity.

2.5.4. Normalized Carbon Efficiency Indicator

To compare environmental impact relative to structural performance [20], a simplified carbon efficiency indicator is introduced:

$$CE = \frac{CO_2}{f_c} \tag{4}$$

where CE is the normalized carbon efficiency (kg CO_2-eq/MPa), CO_2 represents greenhouse gas emissions associated with material production (kg CO_2-eq), and f_c is compressive strength (MPa).

This indicator is used as an interpretative comparative metric to discuss directional differences between conventional OPC systems and lower-carbon alternatives such as SCM-based concrete, LC3, alkali-activated materials (AAMs), and engineered timber systems, emphasizing environmental impact per unit of structural capacity [21].

2.5.5. Life Cycle Impact Intensity per Functional Unit

Sustainability assessment requires functional-unit-based comparison [22]. A simplified life cycle impact intensity indicator can be expressed as:

$$I = \frac{E_{LC}}{FU} \tag{5}$$

where I is the environmental impact intensity, E_{LC} represents life cycle emissions or embodied energy, and FU is the defined functional unit (e.g., 1 m^3 of material, 1 MPa·m^3 structural capacity, or equivalent load-bearing performance).

This normalization is particularly relevant when comparing materials with different densities, strength classes, and design applications.

2.5.6. Service Life Adjustment Factor

Since durability strongly influences long-term sustainability, service life must be incorporated into comparative evaluation [23,24]. A simplified service-life-adjusted indicator may be expressed as:

$$I_{adj} = \frac{E_{LC}}{SL} \tag{6}$$

where I_{adj} is the service-life-adjusted environmental intensity and SL represents the expected service life.

In practice, service life is strongly influenced by resistance to chloride ingress, carbonation, sulfate attack, freeze–thaw cycling, moisture transport, and crack propagation under exposure conditions [25].

Materials with moderate initial emissions but extended durability may therefore demonstrate superior long-term environmental performance compared to alternatives with lower embodied carbon but reduced service life [26].

The analytical relationships presented in this section do not constitute new predictive models, pooled statistical estimators, or formal meta-analytical equations. Instead, they represent established engineering formulations employed here as interpretative normalization tools to compare recurring trends, trade-offs, and sustainability tendencies across heterogeneous literature sources.

3. Results

3.1. Conceptual Synthesis of Environmental Impact and Sustainability Principles

The reviewed studies consistently identify the construction sector as a major contributor to greenhouse gas emissions, primarily due to the intensive production and widespread use of conventional materials such as Portland cement and steel. Across the analyzed literature, these materials are associated with high embodied energy, extensive raw material extraction, and significant CO_2 emissions throughout their life cycle [27–29]. The widespread use of conventional cementitious systems remains a dominant driver of these impacts, reinforcing the urgency of transitioning toward lower-embodied-carbon alternatives [30–32].

Beyond impact quantification, the synthesis of the selected studies reveals that sustainable construction materials are characterized by their capacity to reduce embodied carbon, minimize resource depletion, enhance durability and service life, and enable recyclability or circular resource flows [33,34]. This multidimensional perspective integrates environmental performance with technical reliability and human health considerations [27,35–38], and aligns material innovation with broader sustainability frameworks such as the United Nations Sustainable Development Goals [27,37].

Table 1 summarizes the environmental pressures associated with the construction sector, the core sustainability principles identified in the literature, and the mitigation pathways and assessment tools supporting low-carbon transition.

Table 1. Environmental impact of the construction sector and representative sustainability principles.

Topic	Core Aspects	Representative Metrics/Examples	Ref.
Environmental impact	Energy-intensive cement and steel production; raw material extraction; CDW generation	∼34% global energy use; ∼37% CO_2 emissions	[27,29–32]
Sustainability principles	Embodied carbon reduction; renewable/recycled inputs; durability; circular economy alignment	Representative material pathways: timber, bamboo, recycled aggregates, recycled plastics, and low-carbon cements (application-dependent complementary options)	[33–37]
CO_2 mitigation strategies	Clinker substitution (SCMs, LCCMs); bio-based systems; envelope efficiency	40–75% emission reduction (optimized binders)	[39–42]
Alignment with SDGs	Contribution to SDGs 7, 9, 11, 12, 13; certification integration	LCA, EPDs, LEED, BREEAM	[27,35,43]

The literature further demonstrates that mitigation strategies extend beyond production-phase substitution. Material substitution approaches—such as supplementary cementitious materials, low-carbon binders, and bio-based systems—are consistently identified as effective pathways for reducing CO_2 emissions at the building scale [31,41,42]. These systems have shown substantial emission reduction potential while improving material efficiency and service life [39,40,44]. Their performance is increasingly evaluated through standardized tools such as life cycle assessment and environmental certification schemes [32,43], enabling measurable verification of environmental benefits.

Overall, the evidence indicates that sustainable material transition should be understood as a systemic response to environmental pressures, combining material innovation, durability enhancement, carbon mitigation strategies, and standardized assessment frameworks. This integrated perspective provides the conceptual basis for the detailed material performance analyses presented in the following sections.

3.2. Natural-Based Construction Materials

Natural-based construction materials have gained increasing attention as viable alternatives to conventional high-carbon building materials due to their renewable origin, carbon sequestration potential, and reduced embodied energy [31,33,36,37,42,45]. The studies included in this review examine structural timber systems (CLT and engineered wood), structural bamboo, natural fiber-reinforced cementitious composites (NFRCs), agricultural waste-derived bio-based materials, durability enhancement strategies, and life cycle assessment (LCA) findings.

Global industrial roundwood production reached a record 2.04 billion m^3 in 2022 [46]. Bamboo resources span an estimated 37 million hectares worldwide, concentrated across Asia, Latin America, and Africa, with processing increasingly shifting toward engineered products such as laminated panels and prefabricated components [47]; the global bamboo products market was valued at approximately USD 70–76 billion in 2024 [48].

Likewise, agricultural residues represent a substantial feedstock, with global crop residue generation estimated to exceed 2 billion tonnes per year—including rice straw (370–520 Mt/yr), corn stover (∼1000 Mt/yr), and sugarcane bagasse (∼279 Mt/yr)—of which an estimated 517 Mt of cereal residues remain unexploited annually with demonstrated potential for low-carbon construction products [49,50]. These figures highlight that resource availability differs markedly among natural-based materials and that practical deployment depends on regional supply chains, processing capacity, and standardisation maturity.

Table 2 synthesizes the main technical characteristics, environmental performance outcomes, and key implementation challenges identified across the literature.

Table 2. Natural and bio-based construction materials: main properties, environmental benefits, and main challenges.

Material/System	Typical Use	Properties	Environmental Benefit	Main Challenges	Ref.
Engineered Timber (CLT, LVL, GLT)	Structural systems (mid/high-rise)	High specific strength; structural stability	Biogenic carbon storage; 28–70% lower footprint vs. concrete/steel	Fire/moisture protection; code harmonization	[33,37,42,45]
Structural Bamboo	Structural members and panels	MOR ∼80–120 MPa; high strength-to-weight ratio	Rapid renewability; low embodied energy	Durability and standardization	[33,36,45,51–56]
Hempcrete	Insulation and wall infill	Low thermal conductivity (0.067–0.13 W/m·K)	Often carbon-negative; reduces operational energy	Limited structural capacity	[57–63]
Hemp Fiber Composites	Insulation panels and plasters	Lightweight; good acoustic and thermal behavior	Renewable and recyclable alternative to synthetic fibers	Moisture sensitivity; durability and variability issues	[57,58,63]
Bio-based Materials with Agro-Residues	Lightweight blocks and binders	Improved strength with low thermal conductivity	Waste valorization; reduced embodied emissions	Scalability and material variability	[31,34,35,40,57,61,64,65]
Natural Fiber Cementitious Composites (NFRCs)	Reinforced mortars and panels	Enhanced toughness and crack resistance	Lower emissions than synthetic fibers	Fiber degradation in alkaline matrices	[31,34–36,66,67]

The results in Table 2 confirm that natural-based materials can combine competitive mechanical performance with significant environmental benefits [31,33,36,37,42,45]. Engineered timber systems (CLT, LVL) demonstrate structural adequacy for mid- and high-rise buildings, supported by biogenic carbon storage and lower embodied energy, although outcomes depend on sustainable forest management and end-of-life scenarios [33,37,42,45].

Structural bamboo provides similar sustainability advantages due to rapid renewability and low resource demand [36,51–56], yet mechanical variability and the lack of harmonized standards constrain broader adoption [51,52,54–56].

Natural fiber-reinforced cementitious composites enhance ductility and crack resistance while reducing reliance on synthetic fibers [31,34–36,66,67]. However, durability concerns—particularly fiber degradation and moisture sensitivity—introduce uncertainties in long-term performance despite promising laboratory improvements [34,35,66,67].

Agro-residue-based materials support circular economy strategies by valorizing waste streams and reducing virgin resource use [31,34,35,40,64,65]. While avoided disposal impacts contribute to environmental gains [64,65], scalability, compositional variability, supply logistics, and limited toxicity assessment remain barriers [31,40].

Durability is a cross-cutting determinant of sustainability performance [58,63], as extended service life improves life cycle outcomes. Nevertheless, limited long-term exposure data—particularly under extreme climate conditions—introduce uncertainty.

Life cycle assessments consistently report lower embodied energy and greenhouse gas emissions for bio-based systems compared to conventional materials [31,35,42], although methodological inconsistencies in boundaries, allocation, energy mixes, and end-of-life assumptions limit comparability [37,40]. Harmonized frameworks and regional databases are therefore essential.

Overall, natural-based materials represent a credible decarbonization pathway while maintaining structural functionality [31,33,42,45]. Future research should focus on long-term durability validation, standardized design guidelines, hybrid system integration, and methodological refinement of sustainability assessment.

Table 3 further synthesizes cross-cutting adoption criteria beyond individual material properties by comparing structural capacity, durability evidence, LCA robustness, standardization readiness, and scalability across natural-based construction systems.

Table 3. Qualitative comparative assessment of natural-based construction materials across key adoption criteria.

Material/System	**Strength**	**Durability**	**LCA Robustness**	**Standardization**	**Scalability**
Engineered Timber (CLT/LVL/GLT)	High	Medium	Medium	Medium	Medium
Structural Bamboo	High	Medium	Medium	Low	Medium
Hempcrete	Low	Medium	Medium	Low	Medium
Hemp Fiber Composites	Low	Low	Low	Low	Medium
Agro-Residue Materials	Medium	Low–Medium	Medium	Low	Low–Medium
Natural Fiber Cementitious Composites (NFRCs)	Medium	Low–Medium	Medium	Medium	Medium

Note: Ratings are qualitative and were assigned through comparative synthesis of the reviewed literature, considering recurring evidence on mechanical performance, durability behavior, life cycle assessment (LCA) robustness, standardization readiness, and reported scalability constraints. They represent relative current implementation readiness and evidence maturity, rather than intrinsic material limits or universal substitution potential.

Table 3 indicates that environmental mitigation potential alone does not determine large-scale feasibility. While engineered timber occupies one of the most favorable positions in terms of structural adequacy and adoption readiness, other bio-based systems remain constrained by durability uncertainties, lack of harmonized structural codes, limited long-term exposure data, and supply chain scalability challenges. These findings reinforce the need for integrated technical validation and methodological harmonization to support broader deployment.

Accordingly, these systems are best interpreted as complementary and application-specific low-carbon solutions within diversified construction strategies, rather than universal one-to-one substitutes for conventional cementitious materials.

3.3. Recycled and Reused Construction Materials

The incorporation of recycled and reused materials into construction practices constitutes a central strategy for advancing circular economy principles within the built environment [35,68,69]. Research has increasingly focused on recycled concrete aggregates (RCA), recycled plastics, industrial by-products such as slag and glass, and broader construction and demolition waste (CDW) reuse systems [70–72]. These approaches aim to reduce dependence on virgin resources while minimizing landfill disposal and associated environmental impacts [35,68]. Table 4 synthesizes the mechanical performance characteristics, environmental advantages, and standardization challenges identified across the reviewed literature.

Table 4. Recycled and reused construction materials: performance, environmental contribution, adoption challenges, and key references.

Material Category	Performance Characteristics	Environmental Benefits	Challenges	Ref.
Recycled Concrete Aggregates (RCA)	Moderate reductions in strength and stiffness; suitable for non-structural and, with optimized design, structural applications	Reduces virgin aggregate extraction and CDW landfill; potential embodied carbon reduction	Source variability; adhered mortar; durability control; conservative standards	[35,68,70,72–76]
Recycled Plastics	Lightweight aggregates, panels, and composites; mainly non-structural uses	Mitigates plastic waste; lowers virgin polymer demand	Reduced stiffness; fire performance; long-term durability validation	[33–35,45,71,72,77]
Industrial By-products (slag, glass, tires)	Effective in road bases, soil stabilization, geopolymers, and composites	Infrastructure decarbonization; waste valorization	Leaching risks; market acceptance; regulatory harmonization	[35,68,69,72]
CDW Reuse Systems (System-level)	Transition toward integrated circular construction models	Emission reduction; resource conservation; lifecycle extension	Regulatory disparities; infrastructure and market barriers	[35,68,69]

The evidence summarized in Table 4 indicates that recycled materials can achieve performance comparable to conventional systems when supported by optimized mix design, quality control, and pre-treatment processes [70,71,73,74]. RCA, one of the most extensively studied pathways, show moderate reductions in mechanical properties that can be mitigated through proportion optimization and admixture strategies [70,73–75]. However, source variability and adhered mortar content remain key durability constraints [72,76].

Environmentally, RCA and CDW reuse reduce virgin aggregate extraction and landfill disposal while potentially lowering embodied carbon [35,68]. Yet these benefits depend strongly on transportation distances, processing intensity, and replacement ratios, emphasizing the need for integrated life cycle assessment approaches [72].

Recycled plastics provide dual benefits by addressing plastic waste and reducing virgin polymer demand [35,45], and are increasingly used in lightweight and non-structural applications [33,71,77]. Nonetheless, stiffness, fire performance, and emission behavior require further long-term validation [34,71,72].

Industrial by-products such as slag, glass, and tire residues demonstrate promising performance in infrastructure and geopolymer systems [68,72], contributing to impact reductions [35,69]. However, leaching risks and regulatory harmonization remain adoption barriers [68,69].

At a systemic level, CDW reuse has evolved toward integrated circular economy frameworks [35,68], delivering emission reductions and resource conservation [69], though implementation disparities persist across regions [68].

Overall, recycled materials represent a key pathway toward low-carbon construction [35,68,69]. Future research should prioritize standardized quality control, long-term durability monitoring, harmonized regulations, and comprehensive life cycle assessments accounting for transportation, processing, and end-of-life scenarios [72,76].

To provide a transversal perspective on the relative sustainability performance of natural-based and recycled construction materials, Figure 3 presents a qualitative comparative assessment derived from the synthesis of the reviewed literature. The comparison considers four key dimensions: carbon mitigation potential, circularity contribution, technical maturity, and degree of standardization. These criteria reflect the multi-dimensional framework adopted throughout this review, integrating environmental, technical, and systemic considerations.

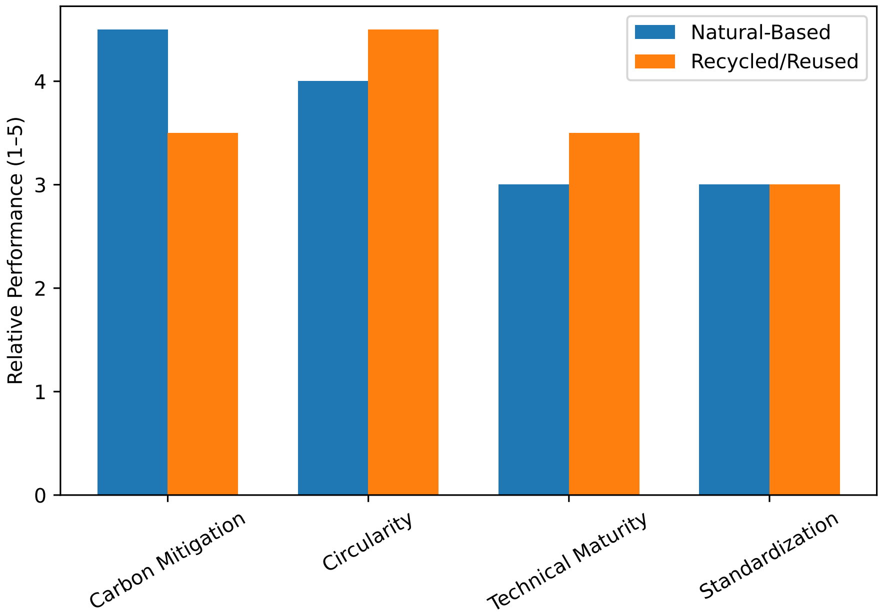

Figure 3. Comparative qualitative assessment of natural-based and recycled construction materials across four sustainability dimensions: carbon mitigation potential, circularity contribution, technical maturity, and degree of standardization. Ratings were derived from comparative synthesis of recurring findings reported in the reviewed literature and are intended as relative evidence-based indicators rather than quantitative performance scores.

Figure 3 presents a qualitative synthesis of the relative positioning of natural-based and recycled materials across important sustainability dimensions, derived from the evidence summarized in Tables 2 and 4. The comparison reflects general performance trends reported in the literature rather than absolute quantitative metrics.

Natural-based materials tend to exhibit higher carbon mitigation potential due to biogenic carbon storage and reduced embodied energy, while recycled materials demonstrate stronger circularity performance through waste valorization and material loop closure. Technical maturity appears broadly comparable, although recycled concrete aggregates benefit from longer industrial implementation, whereas some bio-based systems face durability and standardization challenges.

Overall, the figure highlights that natural-based and recycled materials function as complementary strategies within a systemic low-carbon transition, combining renewable sourcing with circular resource recovery to enhance construction sustainability.

3.4. Alternative and Low-Carbon Cementitious Materials

The cement industry remains one of the most carbon-intensive sectors globally, with ordinary Portland cement (OPC) production responsible for approximately 7–9% of global CO_2 emissions [30,31,41]. These emissions arise primarily from clinker production, which involves both high thermal energy demand and process-related limestone decarbonation [30]. Consequently, reducing clinker content or replacing OPC has become a central strategy in construction decarbonization efforts [31,41]. This section reviews supplementary cementitious materials (SCMs), alkali-activated materials (AAMs), geopolymers, and other low-carbon cementitious materials (LCCMs), incorporating durability and life cycle assessment (LCA) considerations. Table 5 summarizes key characteristics, estimated emission reductions, and implementation challenges.

Table 5. Alternative and low-carbon cementitious materials: key characteristics, approximate impact reductions, and principal challenges identified in the literature.

Material or Strategy	Characteristics	Impact Reduction	Challenges	Ref.
Conventional OPC Impact	High clinker content; energy-intensive production	7–9% of global CO_2 emissions	Market inertia; global dependence	[30,31,41]
SCMs (fly ash, slag, metakaolin, LC3)	Partial clinker substitution; preserved or improved long-term strength and durability	≈40% (LC3); up to ≈60% in optimized blends	Reduced early strength; SCM availability; regional disparities	[30,31,40,41]
Geopolymers/AAMs	Alkali-activated binders from industrial by-products	40–75% reduction vs. OPC (LCA-based)	Activator cost; durability validation; standardization gaps	[30,40]
Other LCCMs (BRPC, YRC, carbonatable cements)	Modified mineralogy to reduce clinker factor or enhance carbonation	≈10–37% reduction	Scalability; kiln adaptation; supply chain transformation	[40,41]
Durability and Service Life	Optimized LCCMs show satisfactory durability and microstructural densification	Extended service life reduces overall life cycle impact	Limited long-term field data	[30,31,40,41]
LCA of Alternative Cements	Production-phase embodied carbon reduction consistently reported	Results sensitive to transport, allocation, electricity mix, carbonation	Need for harmonized regional databases	[40,41]

The evidence confirms that clinker reduction remains the most effective mitigation pathway for cement decarbonization [30,31,41]. SCM-based systems represent the most technically mature and scalable short- to medium-term solutions, achieving substantial emission reductions while maintaining or enhancing long-term durability [30,31,40,41]. However, declining availability of certain industrial by-products and regional disparities in raw material supply pose practical constraints [31].

From a mechanistic perspective, SCM incorporation modifies hydration kinetics through dilution, filler, nucleation, and secondary pozzolanic reactions. These processes progressively consume portlandite, generate additional calcium silicate hydrate (C–S–H), and often refine pore structure, which can improve permeability resistance, chloride resistance, and long-term durability. However, depending on SCM type, fineness, and replacement level, early-age strength development may be slower [30,31,40,41].

Geopolymers and AAMs demonstrate higher theoretical mitigation potential (40–75%) [30,40], but their deployment remains limited by activator cost, environmental burden of alkaline solutions, incomplete long-term durability validation, and lack of harmonized standards [30,40]. Compatibility with existing admixture systems and reinforcement practices requires further validation.

AAM performance strongly depends on precursor chemistry and activator composition. Low-calcium precursors commonly form sodium aluminosilicate hydrate (N-A-S-H)-type gels, whereas calcium-rich systems may additionally generate calcium aluminosilicate hydrate (C-(A)-S-H) phases. These reaction pathways influence setting behavior, strength evolution, shrinkage sensitivity, alkali mobility, and long-term dimensional stability. Carbonation response may also differ substantially from OPC systems and remains an active research topic [30,40].

Overall, macro-scale properties such as compressive strength, stiffness, permeability, durability, and service life are strongly governed by microstructural evolution, including gel formation, pore-size distribution, interfacial transition zone quality, and crack development.

Consequently, microstructural densification and transport control are the main mechanisms linking material design with long-term environmental performance [30,31,40,41].

Other mineralogically modified systems (BRPC, YRC, carbonatable cements) provide moderate emission reductions with potentially greater compatibility with existing kiln infrastructure [40,41]. These approaches may facilitate incremental industrial transition, although scalability and supply chain adaptation remain key barriers [40].

Durability is a critical determinant of overall sustainability performance [30,31,40,41]. Optimized LCCMs can achieve satisfactory durability, and extended service life significantly lowers life cycle impacts [31,40].

Main durability indicators reported in the literature include chloride ingress resistance, carbonation depth, sulfate attack resistance, freeze–thaw stability, water permeability, and crack propagation control. In SCM-rich systems, pore refinement and reduced permeability frequently improve resistance to chloride penetration, although carbonation depth may increase under some low-clinker formulations depending on curing conditions and exposure environment [30,31,40,41].

Nevertheless, durability performance is highly system-specific and depends on pore connectivity, curing regime, cracking susceptibility, exposure environment, and reinforcement compatibility [30,31,40,41].

Nonetheless, very long-term exposure data across diverse climatic conditions remain limited [41].

LCA studies consistently show lower embodied carbon for alternative binders relative to OPC [40,41]. However, outcomes are highly sensitive to transportation distances, allocation of by-products, regional energy mixes, carbonation assumptions, and end-of-life scenarios [40]. The absence of harmonized methodologies complicates cross-study comparison and policy alignment [41].

Overall, alternative and low-carbon cementitious materials constitute a cornerstone of construction decarbonization [30,31,41]. While SCM-based systems currently provide the most scalable pathway, geopolymers and novel mineralogical systems offer long-term transformative potential [40]. Future research should prioritize long-term durability validation under chloride, carbonation, sulfate, and freeze–thaw exposure conditions, low-impact activator development, unified performance standards, and harmonized LCA frameworks to enable reliable sustainability assessment [40,41].

To further clarify the relative positioning of major low-carbon binder families, Figure 4 presents a comparative qualitative assessment of supplementary cementitious materials (SCMs), alkali-activated materials (AAMs/geopolymers), and novel low-carbon cementitious materials (LCCMs). The comparison integrates mitigation potential, technical maturity, scalability, and degree of standardization, reflecting cross-cutting trends identified in the reviewed literature and summarized in Table 5.

Figure 4 shows that SCM-based systems currently offer the most balanced pathway, combining substantial emission reduction potential with high technical maturity and scalability [30,31]. Their compatibility with existing production infrastructure and established standards supports near-term industrial deployment.

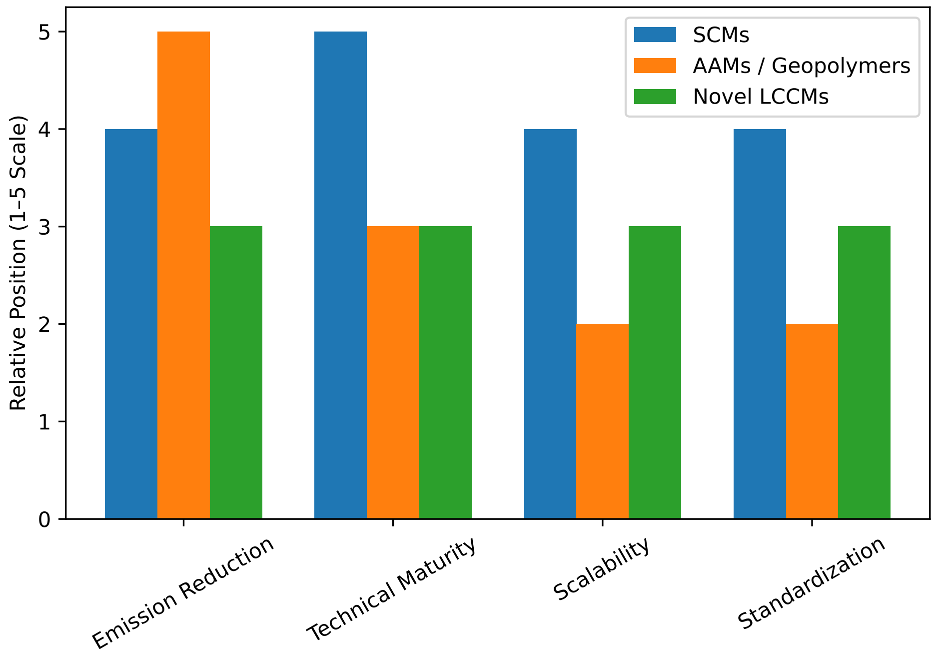

Figure 4. Comparative qualitative assessment of SCMs, AAMs/geopolymers, and novel LCCMs across four main dimensions: emission reduction potential, technical maturity, scalability, and standardization. Ratings were derived from comparative synthesis of recurring findings reported in the reviewed literature and represent relative evidence-based indicators rather than direct quantitative performance values.

AAMs and geopolymers demonstrate higher theoretical mitigation potential, often reported between 40–75% relative to OPC [30,40]. However, their broader adoption is constrained by activator-related environmental burdens, limited long-term durability validation, and incomplete harmonization of standards.

Novel LCCMs, including belite-rich and carbonatable systems, typically achieve moderate emission reductions (≈10–37%) [40,41]. While these systems may offer smoother integration into existing kiln infrastructure, scalability and industrial transformation remain main challenges.

Overall, the comparison reinforces a portfolio-based transition strategy: SCMs provide immediate scalability, AAMs represent high-potential innovation pathways, and novel mineralogical systems offer incremental adaptation routes within existing industrial frameworks [31,41].

3.5. Innovative and Emerging Sustainable Materials

Beyond established bio-based, recycled, and low-carbon cementitious materials, recent research has expanded toward innovative and multifunctional materials designed to enhance performance while reducing environmental impacts across the life cycle [78–82]. These emerging solutions include advanced bio-based composites, self-healing and smart concretes, additive manufacturing technologies, multifunctional energy-efficient materials, and advanced low-carbon high-performance concretes incorporating nanomaterials [30,33,40,42,83]. These systems aim not only to reduce embodied carbon but also to improve durability, optimize resource efficiency, and extend service life. Table 6 summarizes their primary functions, sustainability advantages, and current limitations as identified in the literature.

Table 6. Innovative sustainability pathways in construction materials: category, key benefits, and current limitations identified in the literature.

Innovation Pathway	Category	Primary Function	Key Benefits	Main Limitations	Ref.
Advanced Bio-based Composites	Material System	Natural-fiber composite matrices	Low carbon; renewable inputs; good strength	Moisture sensitivity; scale-up; standards	[78,83–90]
Self-healing Concrete	Functional Material	Autonomous crack repair	Higher durability; lower maintenance	Cost; design complexity; validation	[34,40,79]
3D Printing/Additive Manufacturing	Production Technology	Layered automated construction using optimized mixtures	Less waste; geometry optimization; material efficiency	Quality control; speed; regulation	[33,72,79,80,91–93]
Multifunctional Materials	Material System	Thermal regulation; self-cleaning; pollutant capture	Energy savings; improved air quality	Cost; cycling stability; toxicology	[37,42,79,81,94]
Advanced LCHPCC with Nano-additives	Material System	High-performance low-carbon matrices	High strength; durability; lower impact per unit	Nano cost; safety; dispersion	[30,40,82]

The materials summarized in Table 6 illustrate a transition from carbon-reduction-focused solutions toward performance-driven sustainability strategies [78–82]. Advanced bio-based composites combine natural fibers with bio-based or recycled matrices to reduce fossil inputs while maintaining competitive mechanical performance [78,84–86,88]. However, moisture sensitivity, UV degradation, and limited structural standardization constrain broader application [83,87,89,90].

From a materials perspective, long-term performance additionally depends on fiber–matrix interfacial adhesion, moisture-induced swelling, biodegradation resistance, and variability in natural fiber quality, which may affect durability and structural reliability at scale [84–86].

Self-healing concrete technologies introduce durability as a proactive sustainability strategy by enabling autonomous crack repair through biological or chemical mechanisms [34,40,79]. Although initial costs remain higher, extended service life can offset environmental and economic impacts over time [40]. Nevertheless, large-scale durability validation under real exposure conditions remains limited [34].

Healing efficiency is strongly influenced by crack width, moisture availability, nutrient or reactant transport, bacterial viability or capsule integrity, and precipitation/reaction kinetics during repeated damage cycles. These factors may limit reproducibility under field exposure conditions [34,40,79].

Additive manufacturing technologies further contribute to sustainability by enabling geometric optimization, material efficiency, and integration of recycled or low-carbon binders [33,72,80,91–93]. Despite these advantages, regulatory harmonization, structural verification protocols, and in situ quality control remain critical barriers [79,80].

From a materials-processing perspective, successful scale-up also depends on rheology control, setting kinetics, interlayer bonding quality, dimensional stability, and consistency of printable low-carbon mixtures [33,80].

Smart and multifunctional materials, including phase change materials (PCMs) and photocatalytic systems, extend sustainability to the operational phase by improving thermal regulation and air quality [37,42,81,94]. However, cost, long-term performance stability, and potential toxicological impacts require further assessment [79].

For PCM- and photocatalytic-based systems, long-term efficiency may be influenced by thermal cycling stability, leakage control, surface deactivation, and weathering resistance during service conditions [42,81,94].

Nano-enhanced low-carbon high-performance concretes (LCHPCC) aim to increase strength and durability while reducing material consumption per functional unit [30,40,82].

Reported improvements are commonly associated with pore refinement, nucleation effects, and densification of the interfacial transition zone. However, performance gains are highly sensitive to nanoparticle dispersion stability, agglomeration control, dosage optimization, and rheological changes during mixing. High cost, occupational health concerns, and scale-up reproducibility remain major commercialization barriers [30,40,82].

Overall, innovative and emerging materials expand the sustainability paradigm from emission reduction toward durability enhancement, multifunctionality, and systemic life cycle optimization [40,78,79]. While laboratory-scale results are promising, large-scale adoption depends on regulatory alignment, cost reduction, durability validation, comprehensive environmental and health assessment, and technology readiness maturation [30,37]. Future research should emphasize integrated life cycle evaluation, pilot-scale implementation, technology readiness assessment, and performance validation under realistic service conditions to bridge the gap between experimental innovation and industrial application [40].

To comparatively evaluate the multidimensional contributions of emerging sustainable materials, Figure 5 presents a transversal innovation matrix. The matrix synthesizes qualitative performance trends identified in the literature across key criteria, including mitigation potential, durability enhancement, operational performance benefits, standardization readiness, and scalability.

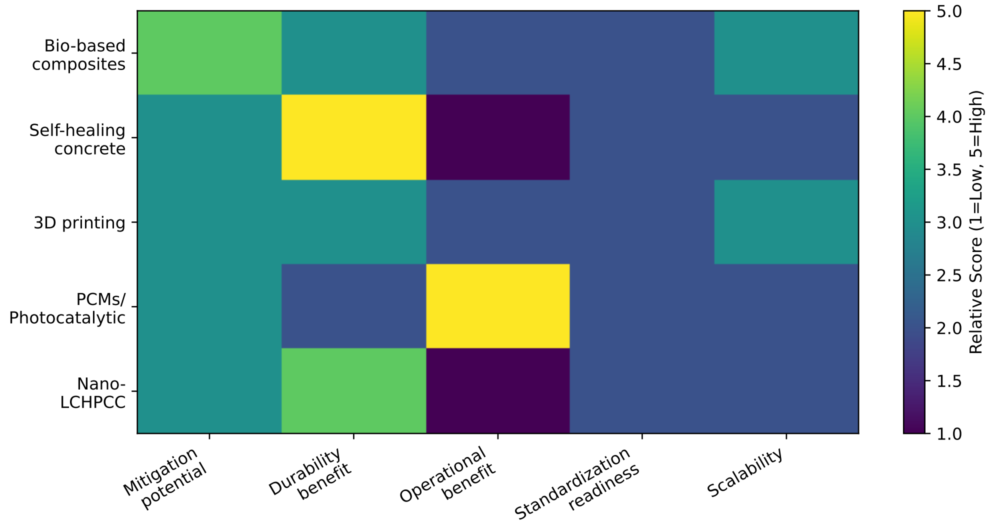

Figure 5. Transversal innovation matrix illustrating relative qualitative scores (1 = low, 5 = high) of emerging sustainable construction materials across key sustainability and implementation criteria. Scores were assigned through comparative synthesis of recurring findings reported in the reviewed literature and reflect current evidence maturity, implementation readiness, and perceived comparative potential. The matrix is intended as an interpretative review tool rather than an empirical ranking or direct quantitative dataset.

Figure 5 highlights that innovative materials exhibit differentiated sustainability strengths rather than uniform performance across criteria. Advanced bio-based composites demonstrate relatively high mitigation potential but face moderate scalability and standardization constraints. Self-healing concrete stands out in durability enhancement, reflecting its capacity to extend service life and reduce maintenance-related impacts.

Additive manufacturing technologies show balanced performance in mitigation and scalability, driven by material optimization and waste reduction capabilities. Smart and multifunctional materials, such as phase change materials and photocatalytic systems, primarily contribute to operational sustainability rather than embodied impact reduction. Meanwhile, nano-enhanced low-carbon high-performance concretes offer significant durability gains but remain limited by cost, dispersion control challenges, and regulatory readiness.

Overall, the matrix underscores that emerging technologies contribute to sustainability through distinct pathways—carbon mitigation, durability extension, operational efficiency, or resource optimization. This reinforces the need for integrated multi-criteria assessment frameworks capable of capturing trade-offs and complementarities among innovation strategies.

3.6. Sustainability Performance Assessment

The evaluation of sustainable construction materials requires integrated performance assessment frameworks encompassing environmental, energy, and health-related dimensions [27,30,32,35,37,40–42,45,79]. Life cycle assessment (LCA), embodied carbon analysis, energy performance evaluation, and comparative sustainability studies represent the principal methodologies used to quantify benefits and trade-offs [27,30,32,35,40–42]. These approaches enable systematic comparison between conventional and alternative materials across production, use, and end-of-life stages [27,32,35,37]. Table 7 summarizes the main assessment dimensions and their typical findings in the literature.

Table 7. Sustainability performance assessment methods applied to sustainable construction materials and typical findings reported in the literature.

Dimension/Method	Application	Typical Findings	Main Focus	Ref.
Life Cycle Assessment (LCA)	Cradle-to-grave evaluation of low-carbon concretes, recycled materials, bio-based systems, and envelopes	Sustainable alternatives generally show lower embodied carbon and primary energy demand than conventional materials	Full life cycle environmental quantification	[27,30,32,35,40–42]
Embodied Carbon Analysis	Comparison of OPC vs. LCCMs, timber/bamboo, and recycled systems	LCCMs: 10–75% reduction; timber/bamboo benefit from sequestration and substitution effects	Greenhouse gas mitigation	[30,40–42,45]
Energy and Resource Efficiency	Evaluation of production, transport, and operational energy performance	Low embodied energy and improved thermal performance reduce operational demand	Energy optimization across life cycle stages	[32,42,45,79]
Sustainable vs. Conventional Comparison	Multi-criteria studies including emissions, toxicity, and indoor air quality	Green materials reduce emissions and may improve human health outcomes	Integrated environmental and health assessment	[27,32,35,37]

Life cycle assessment (LCA) has become the dominant framework for evaluating construction material sustainability [27,30,32,35,40–42].

However, reported outcomes vary substantially according to methodological assumptions. Cradle-to-gate studies generally capture raw material extraction, transport, and manufacturing stages, whereas cradle-to-grave approaches additionally incorporate maintenance, replacement cycles, demolition, recycling, and end-of-life scenarios. Consequently, identical materials may show different mitigation potentials depending on boundary selection [27,30,32,35,40–42].

Low-carbon binders, recycled aggregates, and bio-based systems generally exhibit lower embodied carbon and energy demand than conventional materials [27,30,32,35,40–42].

Embodied carbon analysis provides targeted comparison of OPC with alternative binders and bio-based systems [30,40–42,45]. Reported reductions for LCCMs range from 10% to 75%, while timber and bamboo benefit additionally from sequestration and substitution effects, subject to sustainable sourcing and end-of-life assumptions [42,45].

Energy and resource efficiency assessments extend beyond embodied impacts to operational performance [32,42,45,79]. Bio-based insulation and advanced envelopes reduce heating and cooling demand, and in some cases operational savings offset slightly higher embodied impacts [42,45]. This underscores the importance of integrated embodied–operational evaluation [32].

Comparative studies increasingly incorporate toxicity, indoor air quality, and health-related indicators [27,32,35,37]. Sustainable materials typically reduce VOC emissions, although certain advanced systems require further toxicological validation [35,37].

Despite consistent environmental advantages, methodological variability remains a major limitation [40,41].

Comparability is hindered by inconsistent functional units, including kg CO_2-eq/kg binder, kg CO_2-eq/m^3 concrete, or performance-based units linked to structural capacity and service life. Results are further influenced by allocation methods for industrial by-products, regional electricity mixes, transport assumptions, carbonation credits, and end-of-life modeling. Reported reduction ranges should therefore be interpreted as context-dependent outcomes rather than universal values [41].

Harmonized databases, standardized reporting protocols, alignment with ISO 14040 and 14044 [95] principles and construction-product reporting standards, and dynamic LCA approaches are therefore essential to strengthen reliability and policy relevance [32,35,40,41].

To illustrate the multidimensional nature of sustainability evaluation, Figure 6 presents a conceptual multi-criteria radar model. This representation synthesizes main assessment dimensions commonly applied in sustainable construction materials research, including embodied carbon reduction, operational energy performance, durability, circularity potential, health-related indicators, and economic feasibility.

Figure 6 emphasizes that sustainability performance cannot be adequately captured through a single metric such as embodied carbon. Instead, materials must be evaluated across multiple interrelated dimensions. Environmental performance (embodied carbon and energy), operational efficiency, and durability directly influence long-term life cycle impacts, while circularity potential reflects resource recovery and waste reduction capacity. Health-related indicators and economic feasibility determine practical applicability and market scalability.

The radar representation of Figure 6 highlights the inherent trade-offs among criteria and supports multi-criteria decision-making approaches. By visualizing performance balance rather than isolated optimization, the model reinforces the importance of integrated assessment frameworks in guiding sustainable material selection.

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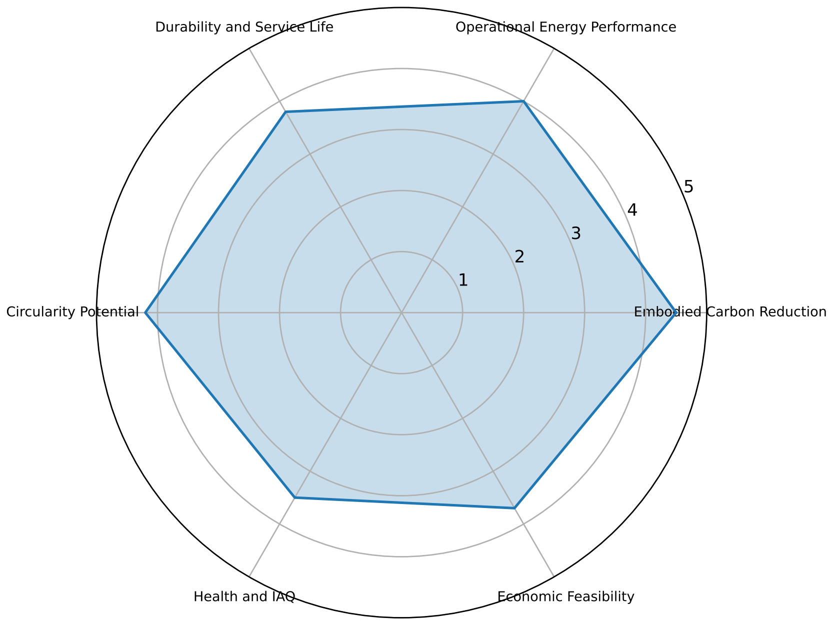

Figure 6. Conceptual multi-criteria radar framework for sustainability assessment of construction materials. The model integrates environmental, technical, circularity, health, and economic dimensions to illustrate the multidimensional criteria commonly considered in the reviewed literature for holistic material comparison. Relative values are schematic and are included solely to visualize trade-offs among criteria; they do not represent empirical measurements or ranked material scores.

3.7. Economic and Social Aspects

Beyond environmental performance, the transition toward sustainable construction materials requires robust evaluation of economic feasibility and social implications [27,30–32,35,37,41,68,96,97]. While many alternative materials demonstrate environmental advantages, their large-scale adoption depends on life cycle cost competitiveness, market acceptance, regulatory incentives, and demonstrated social benefits [27,35,37,68]. The literature increasingly integrates life cycle costing (LCC), economic feasibility analysis of low-carbon cementitious materials (LCCMs) and recycled systems, as well as indoor environmental quality and broader social acceptance dimensions [27,30–32,35]. Table 8 summarizes the important findings reported in the reviewed studies.

Table 8. Economic and social aspects of sustainable construction materials: reported evidence and implications identified in the literature.

Aspect	Reported Evidence	Implications	Ref.
Life Cycle Cost Analysis (LCC)	Many sustainable materials present higher initial costs but lower operational and maintenance expenses	Over the long term, they become economically competitive or advantageous	[27,30–32,35]
Economic Feasibility of LCCMs and Recycled Materials	Clinker substitution with SCMs and waste utilization may reduce raw material costs; AAMs may present higher production costs	Regional pricing, policy incentives, and economies of scale must be considered	[30,31,35,41,96,97]
Indoor Air Quality and Health	Green materials reduce VOC emissions and other indoor pollutants, improving occupant well-being	Indirect benefits include increased productivity and reduced healthcare costs	[27,32,37]

Table 8. *Cont.*

Aspect	Reported Evidence	Implications	Ref.
Social Dimension and Acceptance	Higher acceptance when supported by clear information, certification, and successful case studies; challenges in developing countries due to cost and availability	Public policies, training programs, and stakeholder engagement are required	[27,35,37,68]

The evidence presented in Table 8 confirms that economic and social considerations are decisive for the adoption of sustainable construction materials [27,30–32,35,37,41,68,96,97]. Life cycle cost (LCC) analyses indicate that although many sustainable materials require higher upfront investment, reduced operational, maintenance, and replacement costs can generate favorable long-term economic outcomes [27,30–32,35]. These advantages depend on accurate service-life prediction and discount-rate assumptions [32,35].

The economic feasibility of low-carbon cementitious materials (LCCMs) and recycled systems varies regionally [30,31,35,41,96,97]. Clinker substitution using supplementary cementitious materials (SCMs) and locally available industrial by-products may reduce raw material costs [30,31,96], whereas alkali-activated materials (AAMs) often remain more expensive due to activator production and supply-chain constraints [41,97]. Competitiveness is strongly influenced by economies of scale, carbon pricing, and policy incentives [31,35].

Indoor environmental quality and health are increasingly integrated into sustainability evaluation [27,32,37]. Many green materials reduce VOC emissions and indoor pollutants, potentially improving productivity and reducing healthcare costs [27,32,37]. However, long-term health assessments remain limited for some innovative systems [37].

The social dimension further involves market acceptance, regulatory trust, and equitable access [27,35,37,68]. Adoption increases when supported by certification schemes, standardized testing, and documented case studies [27,35], while higher upfront costs and limited expertise may constrain uptake in developing regions [37,68]. Addressing these barriers requires coordinated policy frameworks, capacity-building initiatives, and stakeholder engagement [27,68].

Overall, sustainable construction materials can deliver long-term financial and societal value [27,30–32,35,37,41,68,96,97], but widespread deployment depends on integrating life cycle costing with environmental assessment and strengthening policy, certification, and educational mechanisms [27,35].

To further conceptualize how economic feasibility, policy support, and social acceptance interact in enabling large-scale implementation, Figure 7 presents an adoption-based framework grounded in innovation diffusion theory. The model illustrates how sustainable construction materials transition from niche applications to mainstream practice under the combined influence of life cycle cost competitiveness, regulatory harmonization, certification mechanisms, and demonstrated socio-environmental benefits.

As shown in Figure 7, early adoption is typically driven by environmentally proactive stakeholders and pilot projects supported by incentives or green procurement policies. However, the critical transition occurs between early adopters and the early majority, where economic reliability, standardized testing, and regulatory trust become decisive. Without demonstrated life cycle cost advantages and institutional validation, sustainable materials may remain confined to niche markets.

Once economies of scale, policy alignment, and market familiarity are achieved, adoption accelerates toward mainstream implementation. This diffusion pathway reinforces that the deployment of sustainable construction materials is not solely a matter of environmental performance but a systemic socio-economic transformation requiring coordinated action among policymakers, industry actors, certification bodies, and end users.

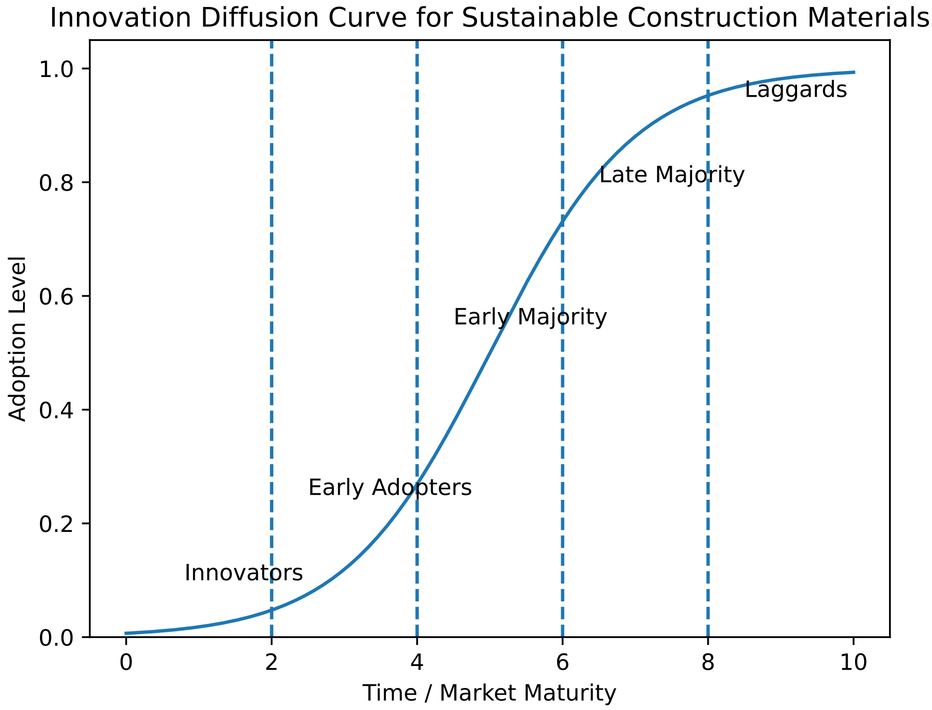

Figure 7. Innovation diffusion curve applied to sustainable construction materials within an economic and social transition context. The progression from innovators to mainstream adoption depends on cost competitiveness, regulatory support, certification schemes, and stakeholder trust.

3.8. Barriers and Challenges

Despite the demonstrated environmental, economic, and functional advantages of sustainable construction materials, their widespread implementation remains constrained by multiple structural barriers [27,30,31,33–35,37,40,41,68,72,79]. These obstacles extend beyond purely technical performance and include regulatory inertia, lack of standardization, market resistance, and uncertainty regarding long-term durability [30,35,72,79]. Understanding these cross-cutting challenges is essential for accelerating the transition toward low-carbon and circular construction systems [33,40]. Table 9 summarizes the main types of barriers identified in the reviewed literature.

Table 9. Main barriers and challenges affecting the large-scale adoption of sustainable construction materials.

Type of Barrier	Description	Consequences	Ref.
Regulatory and Normative	Building codes and standards remain primarily centered on OPC and conventional materials; slow regulatory update processes	Limits large-scale incorporation of LCCMs, recycled materials, and bio-based systems	[30,31,33,37,41,79]
Certification and Standardization	Lack of standardized testing methods and performance criteria for many innovative materials (bio-based, geopolymers, recycled composites)	Design uncertainty; insurance and liability concerns; restricted structural approval	[33,34,40,41,68]

Table 9. *Cont.*

Type of Barrier	Description	Consequences	Ref.
Market and Perception	Concerns regarding performance reliability, cost, and material availability; limited awareness of life cycle benefits	Low adoption rates despite demonstrated environmental advantages	[27,30,35,37,72,79]
Durability and Long-Term Uncertainty	Limited long-term field data for new formulations and bio-based materials	Reluctance from regulators, investors, and industry stakeholders to support unproven solutions	[31,35,40,41,72]

The barriers summarized in Table 9 show that technological maturity alone does not ensure market transformation [27,30,31,33–35,37,40,41,68,72,79]. Regulatory frameworks remain largely centered on OPC-based systems, while slow code revision and limited approval pathways constrain alternative binders, recycled aggregates, and bio-based materials [30,31,33,37,41,79].

The absence of harmonized certification and testing protocols further creates uncertainty in structural approval, insurance, and liability, discouraging adoption in critical applications [33,34,40,41,68]. Market resistance, driven by concerns over reliability, cost stability, and supply chains, often prioritizes upfront investment over life cycle value despite favorable LCA and LCC evidence [27,30,35,37,72,79].

Durability uncertainty—particularly the scarcity of long-term field data—reinforces conservative regulatory and investment decisions [31,35,40,41,72]. Overcoming these constraints requires performance-based regulatory reform, harmonized certification frameworks, policy incentives, and long-term demonstration projects to build confidence and accelerate systemic transformation [27,33,35,37,40,41,79]. Addressing these cross-cutting barriers is essential for unlocking the full decarbonization potential of sustainable construction materials [30,31,40].

To complement the qualitative analysis presented in Table 9, Figure 8 provides a conceptual synthesis of the relative influence level of the main barriers affecting the adoption of sustainable construction materials. The Figure 8 does not represent a quantitative meta-analysis but rather a structured interpretation of the prominence and systemic impact of each barrier category as consistently discussed in the reviewed literature.

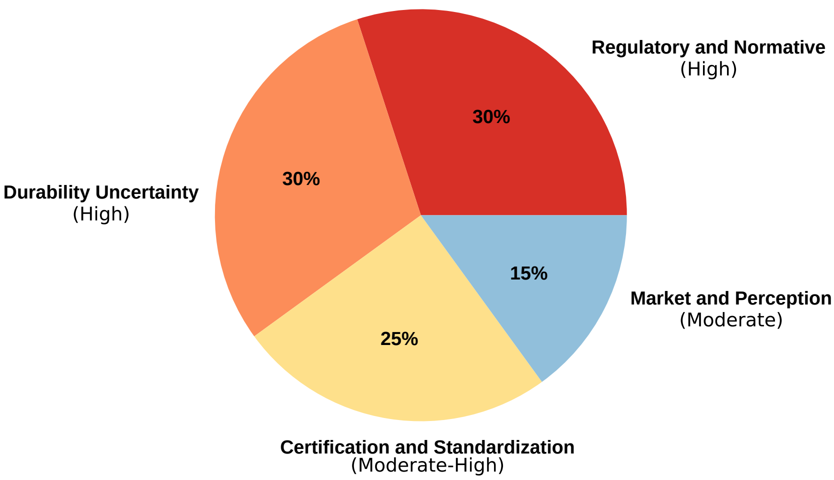

Figure 8. Conceptual representation of the relative influence level of main adoption barriers identified in the literature. The distribution reflects a qualitative synthesis of their systemic impact rather than a statistical frequency analysis.

As illustrated in Figure 8, regulatory and normative constraints, together with durability uncertainty, exert the strongest systemic influence on adoption dynamics. Building codes and approval frameworks remain predominantly structured around conventional OPC-based systems, limiting the incorporation of alternative binders, recycled materials, and bio-based solutions. Simultaneously, the scarcity of long-term field validation data sustains conservative regulatory and investment decisions.

Certification and standardization barriers present a moderate-to-high influence, as the absence of harmonized testing procedures and performance-based approval pathways generates uncertainty in structural design, insurance coverage, and liability assessment. Market and perception-related constraints, while relatively lower in influence compared to regulatory factors, remain significant due to cost sensitivity, supply chain stability concerns, and limited dissemination of life cycle performance data.

Importantly, the figure reinforces the interdependent and systemic nature of these constraints. Regulatory inertia amplifies market hesitation, while durability uncertainty slows certification development and investment confidence. Consequently, overcoming these barriers requires coordinated regulatory reform, harmonized standardization frameworks, policy incentives, and long-term demonstration projects to build stakeholder trust. Addressing these interconnected challenges is essential to enable large-scale decarbonization and circular transformation of the built environment.

3.9. Future Trends and Research Directions

The transition toward sustainable construction materials is entering a phase characterized by systemic integration, digitalization, and performance optimization [27,30,31,33–35,37,40–42,68,69,72,79]. While significant advances have been achieved in low-carbon binders, recycled aggregates, and bio-based systems, emerging research increasingly emphasizes circular economy principles, digital decision-support tools, intelligent materials, and data-driven optimization strategies [33,68,79]. These future directions aim not only to reduce environmental impact but also to enhance functional performance, resource efficiency, and adaptability to regional conditions [31,40]. Table 10 summarizes the principal research lines and innovation pathways identified in the literature.

Table 10. Future trends and research directions in sustainable construction materials.

Trend/Future Line	Description	Opportunities	Ref.
Circular Economy in Materials	Design for recycling; reuse of CDW; upcycling of industrial and agricultural residues	Drastic reduction of waste generation and virgin resource extraction	[33–35,37,68,69,72]
Material Reuse and Closed-Loop Systems	Disassembly systems; structural reuse; pavements and concrete with high recycled content	Emission savings and reduced raw material costs	[35,68,69,72]
Digital Tools and BIM Integration	Integration of LCA data and material databases within BIM platforms for sustainable selection	More informed design decisions and improved impact traceability	[27,68,79]
Advances in LCCMs and Smart Materials	Scaling of LC3, AAMs, LCHPCC, self-healing concrete, and intelligent materials for nearly zero-energy buildings	Combination of low-carbon intensity and high functional performance	[30,31,37,40–42,79]
Artificial Intelligence and Data Analytics	Application of AI for mix optimization, durability prediction, and new material design	Accelerated innovation and local adaptation of sustainable solutions	[33,68,79]

The trends summarized in Table 10 reflect a transition from isolated material innovation toward integrated systemic transformation [27,30,31,33–35,37,40–42,68,69,72,79]. Circular economy strategies—including design for disassembly, large-scale CDW reuse, and upcycling of industrial and agricultural by-products—are expected to play a central role in minimizing landfill disposal and virgin resource extraction [33–35,37,68,69,72], thereby supporting resource security and decarbonization goals [35,68].

Advanced closed-loop systems, modular construction, and high-recycled-content applications demonstrate significant emission and cost-saving potential [35,68,69,72], although their scaling requires reliable tracking systems, certification frameworks, and updated structural assessment protocols [35,72].

Digitalization—particularly BIM integration with LCA databases and EPDs—facilitates real-time sustainability-informed design, enhancing transparency and multi-criteria optimization [27,68,79]. Concurrently, advances in LCCMs, AAMs, LCHPCC, and smart materials are converging with nearly zero-energy building strategies, enabling simultaneous embodied and operational carbon reductions [30,31,37,40–42,79].

Artificial intelligence and data analytics further accelerate mix optimization, durability prediction, and localized adaptation of sustainable materials [33,68,79], although their reliability depends on high-quality datasets and standardized reporting practices [79].

Overall, future research will be defined by interdisciplinary integration—combining circularity, digitalization, advanced material science, and data-driven optimization—supported by harmonized standards and enabling policy frameworks to bridge laboratory innovation with real-world implementation [30,31,33,37,40,79].

To synthesize the strategic orientation of the research pathways identified in Table 10, Figure 9 presents a conceptual relative-priority diagram derived from qualitative analysis of the reviewed literature. The values shown do not represent quantitative bibliometric measurements; rather, they reflect the comparative emphasis, systemic relevance, and long-term transformative potential attributed to each research line across recent studies [31,33,40–42,68,79].

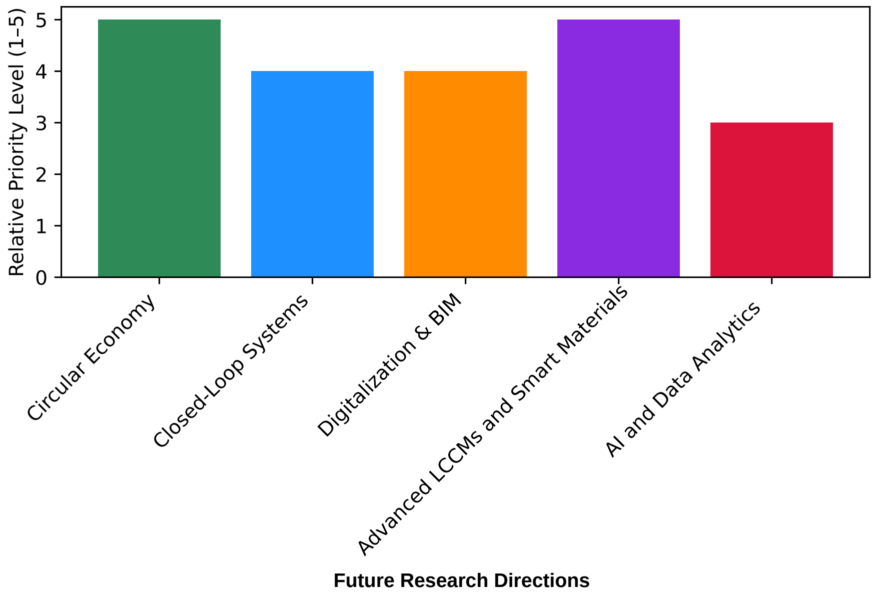

Figure 9. Conceptual relative research priority of emerging sustainability trends in construction materials. The qualitative scale (1–5) was assigned through synthesis of recurring emphasis observed in the reviewed literature together with the potential relevance of each trend for decarbonization, circularity, durability, and implementation challenges. Scores are interpretative comparative indicators and do not represent bibliometric counts or empirical measurements.

Figure 9 indicates that circular economy strategies and advances in low-carbon cementitious and smart materials occupy the most structurally influential positions. These domains directly address embodied carbon reduction, resource efficiency, durability enhancement, and performance optimization, placing them at the core of systemic transformation in the construction sector [31,33,40].

Material reuse and closed-loop systems, together with digital integration through BIM and embedded LCA databases, function as enabling mechanisms that operationalize circularity and improve traceability, transparency, and early-stage decision-making [27,68,79]. Artificial intelligence and advanced data analytics, although comparatively more emergent, demonstrate strong acceleration potential by supporting mix design optimization, durability prediction, and localized adaptation of sustainable materials [33,79].

Overall, the relative-priority distribution reinforces the conclusion that future progress will depend less on isolated material substitutions and more on integrated frameworks that combine circular design, digitalization, advanced material science, and data-driven optimization. This convergence supports a transition toward systemic decarbonization and adaptive, performance-based construction paradigms aligned with long-term sustainability objectives [30,37,40].

4. Discussion

The results presented in Section 3 highlight significant advances across natural-based materials, recycled systems, low-carbon cementitious binders, and emerging sustainable technologies. While these findings demonstrate considerable potential for embodied carbon reduction, resource efficiency, and performance optimization, they also reveal important trade-offs and variability in reported outcomes. Differences in methodological assumptions, regional contexts, material processing routes, and performance metrics complicate direct comparison across studies. To move beyond descriptive synthesis and toward a critical evaluation of systemic implications, the following section integrates the results within a broader sustainability framework.

Section 4, the Discussion, examines comparative performance trends, analyzes environmental and structural trade-offs, evaluates barriers to large-scale implementation, and identifies research gaps and strategic pathways for accelerating the transition toward low-carbon and circular construction systems.

4.1. Cross-Cutting Trends and Innovations in Sustainable Construction Materials

The evolution of sustainable construction materials reflects a transition from single-material substitution strategies toward integrated performance-driven systems [19,27,35,98–112]. Rather than focusing exclusively on embodied carbon reduction, current innovations combine durability enhancement, multifunctionality, circularity, and digital fabrication [19,101,103]. Table 11 synthesizes the dominant material categories, highlighting their technological developments, environmental and technical advantages, and persistent implementation barriers.

The synthesis presented in Table 11 highlights cross-cutting trends redefining sustainable material development [19,27,35,98–112].

Green concrete technologies currently offer the most scalable decarbonization pathway due to infrastructure compatibility and high clinker substitution potential, including additive manufacturing applications [98–103]. Natural materials such as bamboo, hemp, and engineered timber provide biogenic carbon storage and low embodied energy benefits, although broader adoption depends on durability validation and performance-based standards [27,35,104–106].

Table 11. Trends and innovations in sustainable construction materials: environmental and technical advantages and principal challenges.

Category/Material	Examples	Technologies/Systems	Environmental and Technical Advantages	Main Challenges	Ref.
Green Concrete	Fly ash, slag, geopolymer binders	Permeable concrete, self-healing systems, 3D printing	CO_2 reduction (up to 75%); lower energy consumption; enhanced durability	Higher initial costs; technical integration into conventional systems	[98–103]
Natural Materials	Bamboo, hemp, CLT/LVL timber, cork	Engineered timber systems, bio-based panels	Renewable resources; carbon sequestration; low embodied energy	Durability concerns; standardization and code acceptance	[27,35,104–106]
Recycled Materials	Recycled aggregates (CDW), recycled plastics	Recycled concrete blocks, composite panels	Reduced virgin resource extraction; landfill diversion	Quality variability and consistency control	[107–109]
Bio-based Composites	Natural fibers (hemp, flax, jute)	Fiber-reinforced polymeric or cementitious composites	Biodegradability; improved thermal and acoustic insulation	Industrial scalability and long-term durability	[19,104,110]
Smart Materials	Self-healing agents, photocatalytic additives, PCM	Autonomous crack repair systems; energy-regulating envelopes	Extended service life; enhanced energy efficiency	High cost and limited long-term validation	[101,111,112]

Recycled materials primarily strengthen circularity through waste diversion and reduced virgin extraction, yet quality variability remains a structural constraint [107–109]. Bio-based composites combine renewable sourcing with engineered functionality, particularly in lightweight and envelope systems, but require further scalability and long-term validation [19,104,110]. Smart materials introduce adaptive and multifunctional performance—such as self-healing and PCM-enhanced systems—improving life cycle outcomes despite cost and validation challenges [101,111,112].

Overall, the analysis suggests that future sustainable construction will rely on hybridization strategies integrating low-carbon binders, recycled aggregates, bio-based reinforcements, and intelligent functionalities within circular and digitally optimized systems [19,35,98,107,111]. Effective implementation will depend on coordinated regulatory support and industry collaboration to bridge innovation and market adoption [27,103,106,108].

4.2. Comparative Technical and Environmental Performance of Sustainable Materials

A critical dimension of sustainable material assessment lies in the balance between mechanical performance, durability, and quantified environmental benefits [27,35,102–104,106–109]. While many sustainable materials demonstrate reduced embodied carbon, their technical reliability determines practical feasibility in structural and non-structural applications [35,106]. Table 12 provides a comparative synthesis of mechanical resistance, durability considerations, approximate CO_2 reductions, and additional functional properties across representative sustainable materials.

Table 12. Comparative technical and environmental performance of selected sustainable construction materials.

Material/Technology	Mechanical Strength	Durability	CO_2 Reduction (%)	Other Notable Properties	Ref.
Concrete with SCMs	Comparable to OPC when properly designed; improved long-term performance with slag or metakaolin	High durability when mixture optimization is achieved	40–75%	Enhanced chemical resistance	[102,103]
Structural Bamboo	High strength-to-weight ratio	Requires protection against biodeterioration	Up to 80% vs. steel/concrete	Structural flexibility	[27,104]
Recycled Concrete Aggregates (RCA)	Slightly lower than natural aggregates; acceptable for non-critical applications	Dependent on processing and adhered mortar content	20–50%	Construction waste reduction	[107,108]
Recycled Plastics	Suitable for non-structural elements	Good moisture resistance	Variable depending on replacement ratio	Lightweight properties	[108,109]
CLT/LVL Timber	Comparable to concrete and steel in engineered configurations	Long service life with proper maintenance	Significant biogenic carbon sequestration	Good thermal insulation	[35,106]

The comparative analysis in Table 12 confirms that environmental improvements do not necessarily compromise technical performance [27,35,102–104,106–109]. SCM-based concretes present a particularly balanced profile, achieving 40–75% CO_2 reductions while maintaining strength and durability comparable to OPC when properly optimized, with improved chemical resistance supporting long-term reliability [102,103].

Structural bamboo and engineered timber (CLT/LVL) provide high mitigation potential through favorable strength-to-weight ratios and biogenic carbon sequestration, although durability, moisture protection, sustainable sourcing, and end-of-life management remain critical considerations [27,35,104,106].

Recycled concrete aggregates enable 20–50% emission reductions and promote circularity, with performance dependent on processing quality and mix optimization [107,108]. Recycled plastics contribute mainly to waste diversion and lightweight non-structural applications, with environmental benefits influenced by substitution ratios and processing methods [108,109].

Overall, the most effective sustainable materials combine structural adequacy, durability, and measurable carbon mitigation [35,102,104,107]. Trade-offs between mechanical reliability, service life, and emission reduction should be assessed using functional-unit-based life cycle approaches, prioritizing integrated optimization to ensure safety and long-term performance [35,102,103,106].

4.3. Life Cycle Environmental Impacts of Recycled and Natural Materials

A comprehensive sustainability evaluation must consider embodied energy, greenhouse gas emissions, recyclability, and end-of-life performance [79,113–124]. Recycled and natural materials often derive their environmental advantage not only from lower production impacts but also from circularity and carbon storage mechanisms [121,122]. Table 13 synthesizes the life cycle environmental performance of selected recycled and bio-based materials commonly applied in construction.

Table 13. Life cycle environmental impacts of recycled and natural construction materials.

Material/Strategy	Embodied Energy	CO_2 Emissions	Recyclability	End-of-Life Strategy	Primary Environmental Benefit	Ref.
Recycled Aggregates (RCA, CDW)	Lower than natural aggregates due to avoided extraction and processing	Significant reduction compared to virgin aggregates	High	Reusable in new concrete, road bases, and structural fills	Reduced virgin resource extraction; landfill diversion; lower carbon footprint	[113–117]
Concrete with Recycled Aggregates	Lower production energy when partially or fully substituting natural aggregates	Emission reduction proportional to substitution rate	Medium–High	Dependent on processing quality; potential for secondary reuse as aggregate	Natural resource conservation; lower production energy and emissions	[79,113,115,118]
Recycled Plastics	Variable; generally low when replacing mineral aggregates	Reduction associated with avoided virgin polymer production	High	Mechanical recycling or reuse in composite applications	Reduction of plastic pollution; decreased virgin polymer use; lightweight properties	[119,120]
Reclaimed/Bio-based Timber	Very low compared to steel or concrete	Negative biogenic carbon balance due to carbon storage	High	Reuse in structural elements; biodegradation or energy recovery	Carbon sequestration; renewable sourcing; low environmental impact	[121]
Agro-residues (ashes, fibers)	Very low due to waste-based origin	Significant reduction compared to conventional binders or aggregates	High	Reintegration into production cycles or controlled biodegradation	Agricultural waste valorization; reduced open burning and virgin aggregate extraction	[122,123]
Recycled Glass	Lower than virgin glass production	Reduced emissions through substitution of sand or cement	High	Closed-loop recycling without significant quality loss	Reduced natural sand extraction; landfill reduction	[114,124]

The life cycle comparison in Table 13 confirms that recycled and natural materials provide environmental advantages through complementary pathways, including reduced embodied energy, enhanced circularity, and carbon storage [79,113–124].

Recycled aggregates (RCA and CDW-derived materials) lower emissions mainly by reducing virgin extraction and landfill disposal, exhibiting lower embodied energy than natural aggregates when transport is optimized [113–117]. Concrete incorporating recycled aggregates maintains acceptable performance while extending material loops within the construction sector [79,113,115,118]. Recycled plastics contribute to waste mitigation and fossil resource conservation, although outcomes depend on processing and substitution ratios [119,120].

Bio-based and reclaimed timber stands out for its carbon sequestration capacity and potential negative biogenic balance when sustainably managed [121]. Agro-residues (ashes and fibers) combine very low embodied energy with waste valorization benefits [122,123], while recycled glass enables repeated recycling and reduces pressure on natural sand extraction [114,124].

Overall, the most effective life cycle strategies integrate low embodied impacts, high recyclability, and carbon storage [113,121,122]. Nevertheless, results remain context-dependent, influenced by logistics, regional energy mixes, and end-of-life management [117,118]. Future research should advance dynamic, region-specific LCA models and hybrid systems that simultaneously enhance circularity and decarbonization [79,123].

4.4. Barriers to Large-Scale Adoption of Recycled and Natural Materials

Despite the well-documented environmental and technical benefits of recycled and natural construction materials, their large-scale implementation remains uneven across regions [36,79,121,125–134]. Adoption is influenced not only by material performance but also by regulatory, economic, logistical, and socio-cultural factors [79,125,129]. Table 14 synthesizes the principal barriers limiting the widespread deployment of recycled aggregates, bio-based systems, and other circular materials.

Table 14. Main barriers to the mass adoption of recycled and natural construction materials.

Main Barrier	Description	Example	Impact on Adoption	Ref.
Regulatory and Limited Standards	Lack or inconsistency of codes and technical specifications	Absence of clear parameters for RCA/CDW quality and durability	High	[36,125,126]
Market Perception	Concerns about structural performance and long-term reliability	Cultural resistance to non-conventional materials	Medium	[125,127]
Material Variability and Quality	Heterogeneity in physical and chemical properties	Differences depending on origin and processing methods	Medium–High	[79,128]
Initial Costs and Logistics	Higher upfront costs due to processing and supply chain adjustments	Transportation distances influencing environmental footprint	Medium	[129,130]
Regional Availability	Limited local supply and infrastructure	Scarcity of recycling plants or certified timber sources	Medium	[121,131]
Lack of Local LCA Information	Insufficient region-specific and long-term assessments	Scarcity of localized LCA studies for emerging materials	Medium	[132,133]
Social and User Acceptance	Limited awareness and stakeholder confidence	Need for educational campaigns and supportive public policies	Medium	[125,134]

The barriers summarized in Table 14 indicate that the transition toward circular and bio-based construction systems is constrained primarily by systemic and institutional factors rather than technical limitations [36,79,121,125–134]. Regulatory inertia remains the dominant obstacle, as building codes are largely oriented toward OPC-based systems and lack harmonized standards for recycled aggregates and bio-based materials [36,125,126]. This absence of clear performance criteria generates uncertainty among engineers, insurers, and policymakers [36].

Material variability and heterogeneity further limit confidence in structural reliability, particularly without robust quality control and certification systems [79,128]. Market perception and cultural resistance, combined with limited dissemination of life cycle evidence, also slow adoption despite documented benefits [125,127]. Economic and logistical constraints—including processing costs, transport distances, and regional supply limitations—add additional complexity [121,129–131].

Moreover, the scarcity of region-specific and long-term LCA data complicates benefit quantification and policy alignment [132,133]. Social acceptance remains essential, requiring awareness campaigns, incentives, and green procurement strategies to build stakeholder confidence [125,134].

Overall, overcoming these challenges demands coordinated regulatory reform, standardized quality frameworks, localized supply chains, economic incentives, and stakeholder engagement to unlock the full environmental and circular potential of recycled and natural materials [36,121,125,129,133].

4.5. Integrated Strategic Discussion

The synthesis of Tables 11–14 confirms that sustainable construction materials are transitioning from isolated technological alternatives toward components of a systemic transformation structured around three interdependent pillars: decarbonization, circularity, and durability.

Decarbonization strategies—particularly low-carbon binders, green concrete technologies, and engineered timber systems—demonstrate that embodied carbon reductions ranging from 20% to over 75% can be achieved without compromising structural performance (Table 12). When properly optimized, these materials not only reduce emissions but may also enhance durability and chemical resistance, indicating that environmental performance and mechanical reliability are not mutually exclusive objectives.

From a life cycle perspective, complementary environmental mechanisms further strengthen this transition (Table 13). Recycled materials primarily contribute through landfill diversion and conservation of virgin resources, whereas bio-based systems provide carbon sequestration and inherently low embodied energy. These distinct but synergistic pathways suggest that hybrid material systems—combining recycled mineral components with bio-based reinforcements—may maximize overall sustainability performance across the full life cycle.

Durability emerges as a strategic multiplier. Smart and multifunctional materials extend service life, reduce maintenance, and enhance operational efficiency, thereby shifting sustainability assessment from short-term emission reduction toward long-term life cycle optimization. This reinforces a central insight of this review: sustainability must be evaluated through functional-unit and life cycle-based frameworks. Materials achieving moderate initial carbon reductions but superior durability may outperform alternatives offering higher short-term savings but uncertain long-term reliability.

Despite these advances, large-scale implementation remains constrained by systemic barriers (Table 14). Regulatory inertia, limited standardization, market skepticism, and material variability collectively create a structural gap between technological innovation and policy adaptation. This misalignment slows diffusion even when environmental and technical feasibility are well established.

To conceptually synthesize these interacting dimensions, Figure 10 presents an integrated strategic framework linking the three pillars—decarbonization, circularity, and durability—with enabling mechanisms and systemic constraints that determine transition feasibility.

As illustrated in Figure 10, decarbonization operates through material innovation (e.g., SCM-based binders and engineered timber), circularity through resource recovery and hybridization, and durability through service-life extension and multifunctional performance. These pillars are mutually reinforcing: enhanced durability amplifies carbon mitigation benefits, circular strategies reduce upstream production impacts, and low-carbon formulations enable scalable emission reductions.

The framework further emphasizes that integration—rather than simple material substitution—is the defining principle of sustainable construction. Convergence among circular strategies, low-carbon cementitious systems, digital tools, and hybrid structural solutions must be supported by regulatory reform, standardized validation protocols, and transparent life cycle databases. Without such systemic coordination, technically superior materials may remain confined to niche applications.

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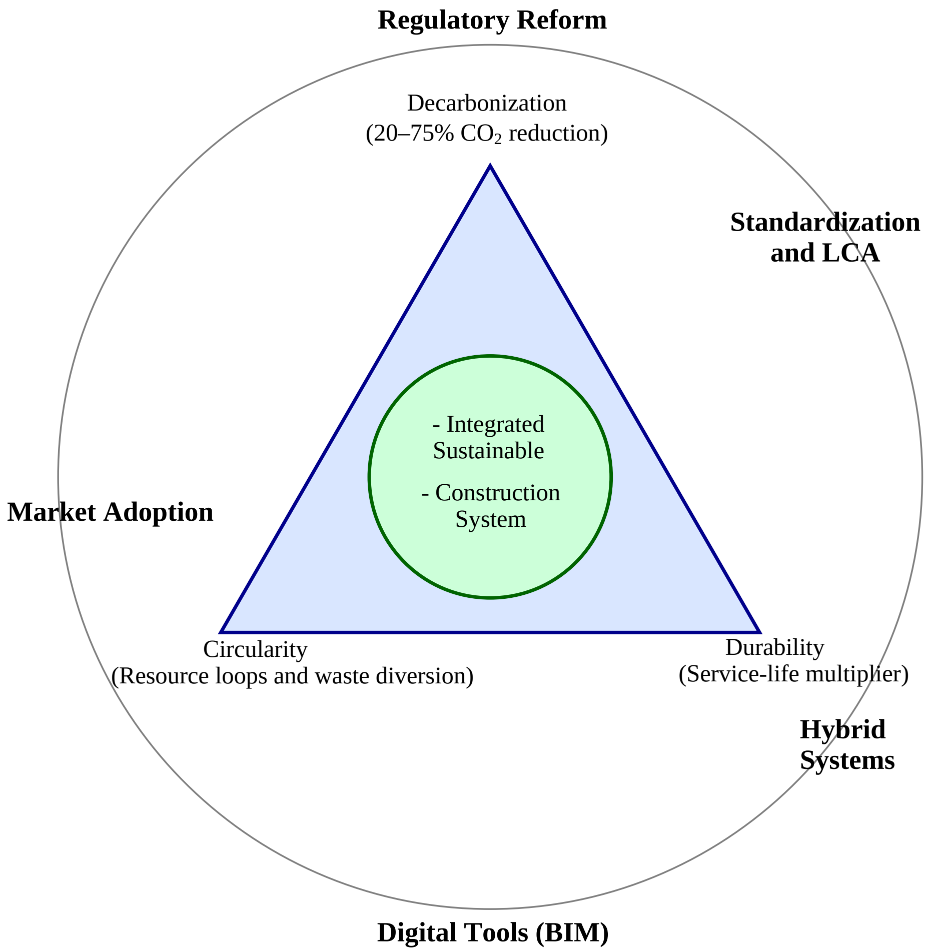

Figure 10. Integrated strategic framework for sustainable construction materials, structured around decarbonization, circularity, and durability as mutually reinforcing pillars, moderated by systemic barriers and enabling mechanisms.

Ultimately, the transition toward sustainable construction materials depends on aligning technological innovation with institutional adaptation. When decarbonization, circularity, and durability are addressed simultaneously within performance-based and life cycle-oriented frameworks, the built environment can achieve durable environmental, economic, and socio-social benefits.

4.6. Comparison with Representative State-of-the-Art Reviews on Sustainable Construction Materials

A critical examination of existing review articles reveals that research on sustainable construction materials has expanded significantly over the past decade. However, most prior reviews tend to focus on specific material families (e.g., geopolymers, recycled aggregates, bio-composites) or isolated assessment dimensions such as embodied carbon or life cycle assessment (LCA), without systematically integrating mechanical performance, durability, environmental metrics, and adoption barriers within a common comparative framework.

Table 15 summarizes representative review works relevant to sustainable construction materials, highlighting their main focus areas, methodological scope, and key limitations. While early contributions such as [72,134] provided foundational insights into LCA and sustainable concrete strategies, they did not comprehensively address bio-based systems, smart materials, or circular economy integration. More recent reviews (2018–2025) increasingly incorporate low-carbon cementitious materials (LCCMs), recycled systems, and bio-based composites; however, many remain material-specific and lack cross-comparative synthesis or structured PRISMA-based screening.

The present systematic review seeks to comparatively synthesize natural materials (engineered timber, bamboo, hemp-based systems), recycled materials (RCA, plastics, industrial residues), alternative low-carbon binders (SCMs, geopolymers), and innovative smart technologies (self-healing systems, multifunctional materials, additive manufacturing) within an integrative comparative framework. Beyond environmental performance, this study explicitly evaluates thermo-mechanical behavior, durability implications, scalability constraints, and regulatory barriers, providing a multi-dimensional synthesis aligned with circular economy and sustainability transition strategies.

Table 15. Comparison of representative state-of-the-art reviews on sustainable construction materials and the positioning of this study.

Work	Main Focus	Methodology	Strengths	Limitations	Contribution of This Work
[134]	LCA of conventional materials	Review of case studies	Early environmental benchmarking	No coverage of emerging low-carbon or bio-based systems	Extends assessment to recent sustainable material families with performance integration
[72]	Sustainable cement-based materials	Critical review	Comprehensive SCM and durability analysis	Cement-focused; limited cross-material comparison	Embeds cement systems within a broader multi-material framework
[100]	Geopolymers and circular economy	Thematic review	Strong emission-reduction analysis	Limited scope beyond AAMs	Integrates geopolymers with timber, recycled, and smart systems
[104]	Bio-based composites	Narrative review	Material-science depth	Limited building-scale and LCA linkage	Connects bio-based materials to structural and envelope performance
[115]	Embodied carbon meta-analysis	Systematic review	Robust carbon quantification	Limited durability and adoption discussion	Links carbon data with mechanical, durability, and barrier analysis
[68]	Recycled construction materials	Systematic review	Broad waste valorization overview	Limited thermo-mechanical comparison	Integrates recycled materials within cross-category sustainability evaluation
This Work	Natural, recycled, LCCMs, bio-based, and smart materials	PRISMA 2020 systematic review	Multi-dimensional comparison (performance, LCA, barriers)	Focus on journal articles; limited long-term field validation	Provides cross-category comparative synthesis for strategic low-carbon material transition assessment

To further position this review within the evolving research landscape, Table 16 compares the thematic coverage of representative state-of-the-art reviews with the scope of the present study. The comparison demonstrates that while recent reviews increasingly acknowledge sustainability and circular economy concepts, few simultaneously address natural-based systems, recycled materials, low-carbon binders, innovative smart technologies, mechanical performance, environmental assessment, and adoption barriers within a structured and systematic methodology.

Table 16. Comparison of this work with representative state-of-the-art reviews on sustainable construction materials.

Work	Natural	Recycled	LCCMs	Innovative	Thermo-Mechanical	LCA	Period
[72]		X	X		X	X	2000–2019
[104]	X				X	X	2005–2019
[100]		X	X		X	X	2010–2021
[115]	X	X	X			X	2000–2020
[68]		X			X	X	2015–2024
[33]	X	X	X	X	X	X	2010–2024
This Work	X	X	X	X	X	X	2018–2025

Overall, the comparative analysis highlights a clear evolution in the literature from material-specific or carbon-focused reviews toward more integrative sustainability assessments. Nevertheless, fragmentation persists in linking mechanical reliability, durability, environmental impact, and real-world adoption barriers.

Although full quantitative harmonization remains constrained by heterogeneous reporting practices, this review provides a structured comparative synthesis that uses explicit thematic coverage matrices and evidence integration across studies published between 2018 and 2025.

This approach supports strategic decision-making in sustainable construction and identifies priority research directions for accelerating the transition toward low-carbon, resource-efficient built environments.

4.7. Temporal and Thematic Evolution of Scientific Production on Sustainable Construction Materials

The temporal distribution of the publications included in this systematic review reveals a clear and sustained growth trend in recent years, highlighting the increasing scientific interest in sustainable construction materials. As shown in Figure 11, scientific production remained relatively low between 2018 and 2020, representing less than 1% of total publications per year. This initial stage can be considered an emerging phase, where research activity was still limited and fragmented.

A significant increase began in 2021, when the proportion of publications rose to approximately 7%, followed by a continuous upward trend in 2022 (≈12%), 2023 (≈14%), and 2024 (≈15%). This progressive growth reflects the consolidation of sustainable construction materials as a strategic research field, driven largely by global environmental concerns, regulatory pressures, and the urgent need to reduce the carbon footprint associated with the construction sector.

Notably, 2025 represents the most productive year, accounting for approximately 37% of the total publications analyzed (Figure 11). This remarkable increase suggests an accelerated expansion of research efforts, likely associated with the strengthening of international sustainability agendas, advances in material engineering technologies, and increased investment in green construction solutions. Furthermore, it is particularly relevant that during the first two months of 2026, the number of publications has already reached levels comparable to or exceeding those observed in entire previous years, indicating that the growth trend is not only continuing but accelerating. This behavior suggests that sustainable construction materials have transitioned from an emerging research topic to a mature and priority scientific domain with strong future projections.

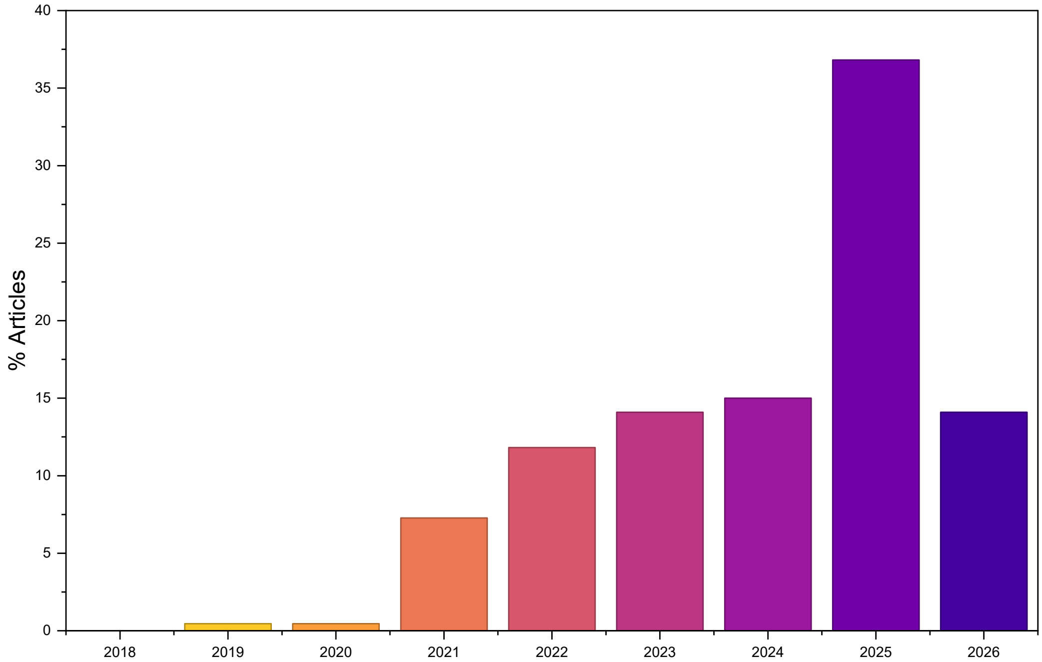

Figure 11. Temporal evolution of scientific production on sustainable construction materials (2018–2026).

From a thematic perspective, the distribution of publications according to PRISMA classification codes reveals that research in this field is inherently multidisciplinary. As illustrated in Figure 12, the dominant subject area is Engineering, which accounts for 30.5% of the publications, followed by Materials Science (20.9%) and Environmental Science (20.5%). These three areas together represent more than 70% of the total scientific output.

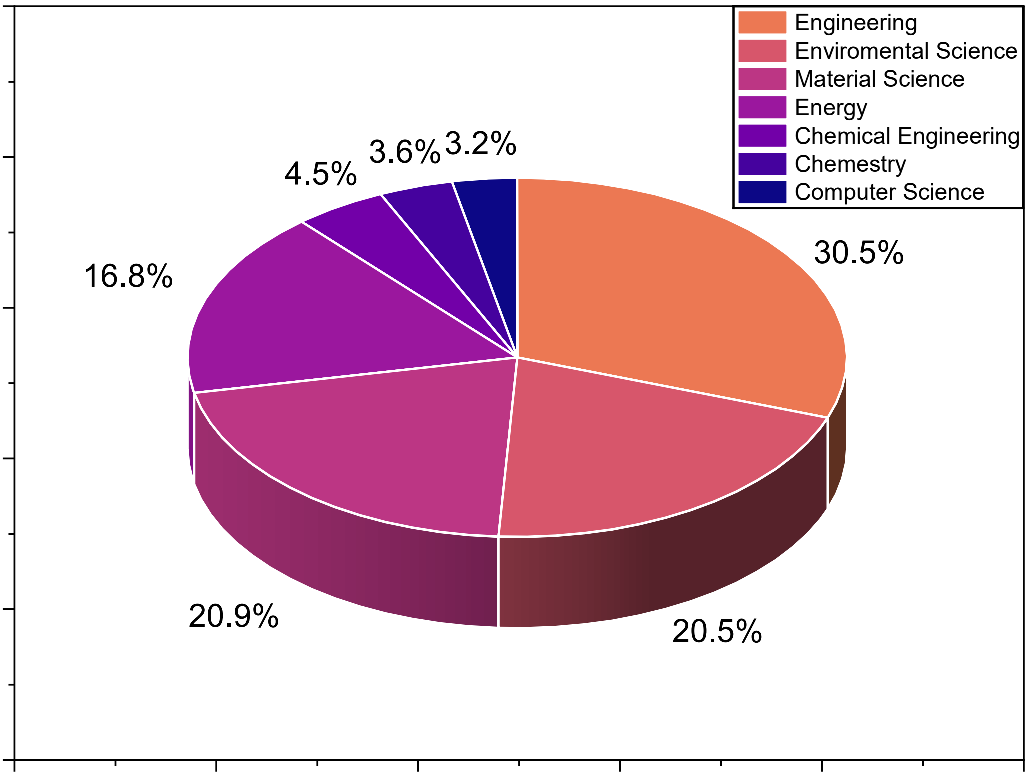

Figure 12. Subject area distribution of publications on sustainable construction materials.

This distribution highlights the technological and environmental duality that characterizes sustainable construction materials. Engineering plays a central role in the design, optimization, and large-scale implementation of innovative materials, while Materials Science contributes to understanding the structural, mechanical, and durability properties of sustainable alternatives. At the same time, Environmental Science reflects the growing emphasis on evaluating environmental performance, including life cycle assessment, carbon emissions reduction, and resource efficiency. This confirms that sustainability in construction is no longer viewed solely as a materials challenge, but as an integrated technological and environmental transition.

However, this thematic dominance has evolved over time, as shown in Figure 13, which presents the annual distribution of publications by subject area. Between 2021 and 2023, Materials Science was the leading research area, reflecting an initial focus on developing and characterizing new sustainable materials, such as recycled composites, bio-based materials, and alternative binders. This stage corresponds to a foundational phase centered on material innovation.

Starting in 2024, Engineering surpassed Materials Science as the main contributing discipline, indicating a shift from material development toward practical implementation, performance optimization, and integration into construction systems. This transition suggests that research efforts have moved beyond laboratory-scale material characterization toward real-world applications and engineering solutions.

Most notably, 2025 marks a turning point, with a substantial increase in publications across multiple disciplines, confirming the emergence of sustainable construction materials as a central and rapidly expanding research priority. This surge reflects the convergence of technological readiness, environmental urgency, and policy-driven demand for sustainable infrastructure.

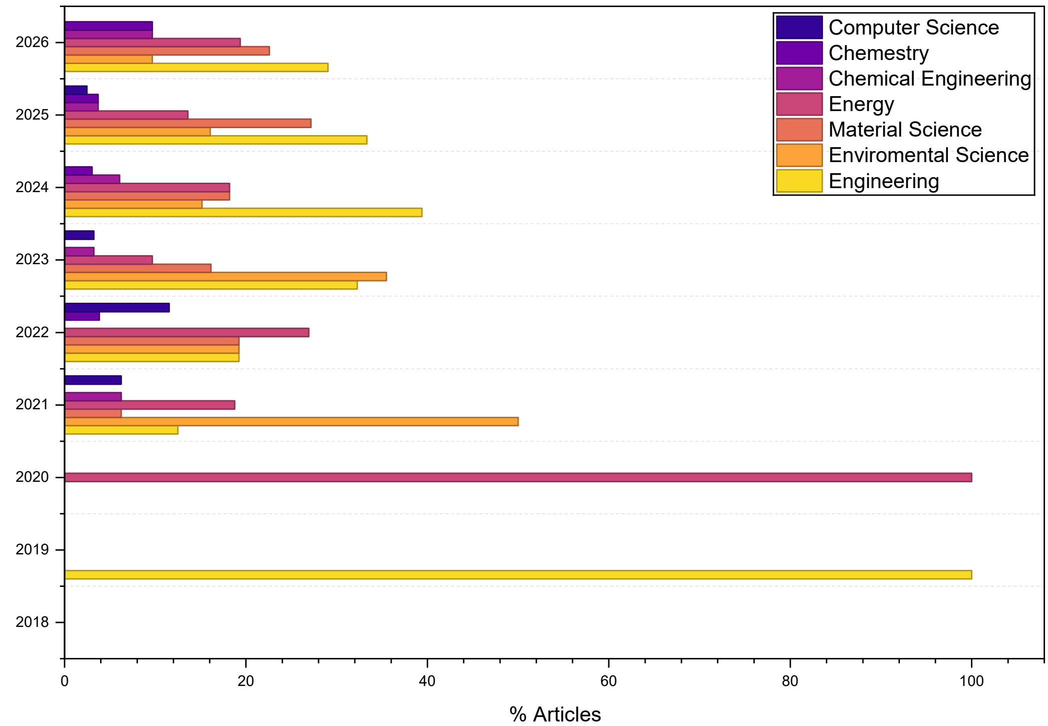

Figure 13. Annual distribution of publications by subject area in sustainable construction materials research (2018–2026).

Overall, the combined analysis of Figures 11–13 demonstrates that research on sustainable construction materials has evolved through three main phases:

1. Emergence phase (2018–2020): limited scientific production and exploratory research.
2. Development phase (2021–2023): consolidation driven primarily by Materials Science.
3. Expansion and implementation phase (2024–2026): rapid growth led by Engineering, with strong multidisciplinary integration.

This evolution reflects a broader paradigm shift in the construction sector, where sustainability has become a fundamental driver of innovation rather than a secondary consideration. The accelerated growth observed in recent years suggests that sustainable construction materials will continue to play a critical role in achieving global environmental targets and advancing the transition toward low-carbon and resource-efficient built environments.

5. Conclusions

This systematic review confirms that sustainable construction materials play a critical role in the decarbonization of the built environment. The construction sector remains a major contributor to global energy consumption and CO_2 emissions, primarily due to the widespread use of ordinary Portland cement and steel. However, recent advances demonstrate that viable low-carbon alternatives are technically feasible and increasingly mature.

Low-carbon cementitious materials, bio-based systems such as engineered timber and bamboo, and recycled construction materials show significant potential to reduce embodied carbon while maintaining adequate mechanical performance when properly designed. Reported emission reductions range from moderate to substantial depending on material type, system boundaries, and life cycle assessment assumptions. Durability and service life are key determinants of long-term environmental performance.

Circular economy strategies, including the reuse of construction and demolition waste and the incorporation of industrial by-products, further strengthen sustainability outcomes. Emerging technologies such as smart materials and additive manufacturing expand this potential by enhancing durability, resource efficiency, and operational performance.

Despite demonstrated environmental and technical benefits, large-scale adoption remains limited by regulatory inertia, lack of standardization, durability uncertainties, and market resistance. Therefore, the transition toward sustainable construction depends not on isolated material substitution but on integrated systems that combine decarbonization, circularity, and durability within life cycle-based assessment frameworks.

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