

Assessment and Quantification of Embodied Energy and Carbon Emissions of Sustainable Construction Materials: A Critical Review

Gopinath Nallagarla¹, Dr.Jerripotu Gopal Rao², Dr.P.Sundar Kumar³,

¹Research Scholar, Almbani General Contractors, KSA (Kingdom of Saudi Arabia),

Email: gopinathnallagarla@gmail.com

²Professor, Vignan University, Vadlamudi, Guntur-522213, Andhra Pradesh. Email: drjg_civil@vignan.ac.in

³Associate Professor, Vignan University, Vadlamudi, Guntur-522213, Andhra Pradesh.

Email: pskumarphd@gmail.com

Abstract

The construction sector depends on energy- and resource-intensive materials whose production contributes substantially to greenhouse-gas emissions and other environmental pressures. As operational energy demand decreases through improved building efficiency and cleaner energy systems, the embodied impacts associated with material production become increasingly important in design and procurement decisions. This paper critically reviews and quantifies reported embodied-energy and embodied-carbon values for selected sustainable construction materials, with emphasis on low-carbon cementitious materials, recycled materials, earth-based materials, bio-based materials and engineered sustainable products. The study uses a secondary-data assessment framework based on values reported in the Inventory of Carbon and Energy (ICE) database and peer-reviewed literature, supplemented by recent evidence on emerging construction materials and embodied-carbon assessment. A cradle-to-gate material boundary is used as the principal reporting basis; however, the review explicitly examines how system boundary, geographic context, electricity mix, production technology, transport, moisture content, allocation procedures and carbon-accounting conventions influence reported values. Representative values compiled in the source manuscript indicate wide variation among sustainable materials, with particularly low reported embodied-energy and carbon coefficients for some industrial by-products and minimally processed earth materials, while processed bio-based and engineered products can show higher mass-normalized energy values despite potentially favorable functional performance. The analysis demonstrates that embodied energy and embodied carbon are related but not interchangeable indicators: carbon intensity depends on the energy source as well as process emissions, while allocation assumptions can strongly influence the apparent burdens of industrial by-products such as fly ash and ground-granulated blast-furnace slag. For bio-based materials, fossil emissions and biogenic carbon storage require separate treatment. The review also identifies substantial data gaps for emerging materials and cautions against assigning universal coefficients to material categories without specifying production route, geography, system boundary and accounting method. The paper provides a structured basis for material-level embodied-impact assessment and identifies the data harmonization requirements that should precede project-specific life cycle assessment.

Keywords: embodied energy; embodied carbon; sustainable construction materials; carbon emissions; secondary data; material sustainability; allocation; biogenic carbon; construction materials

1. Introduction

The environmental performance of buildings is strongly influenced by the materials required to construct them. Cement, steel, masonry products, insulation, timber products and other construction materials require extraction, processing, manufacturing and transportation before they can be incorporated into a building. These upstream activities consume energy and generate greenhouse-gas emissions, and their significance becomes more visible as operational energy demand is reduced through efficient envelopes, improved building services and cleaner electricity systems.

Embodied energy describes the energy associated with the provision of a material or product, including relevant extraction, processing, manufacturing and transport stages according to the selected system boundary. Embodied carbon is commonly expressed as carbon-dioxide equivalent emissions associated with the same defined life-cycle stages. The two indicators are related because energy-intensive processes frequently generate emissions, but they are not equivalent. The carbon intensity of energy depends on the electricity and fuel mix, while some materials—most

notably Portland cement—also have substantial process emissions that arise from chemical reactions rather than energy use alone.

Sustainable construction materials encompass a broad and heterogeneous group rather than a single material class. The category includes industrial by-products used as binders, recycled materials, low-processing earth materials, renewable bio-based materials and engineered products designed to reduce resource or carbon intensity. Their sustainability performance cannot therefore be inferred from material labels alone. Production technology, feedstock, transport distance, moisture content, energy source, treatment, allocation procedure and end-of-life assumptions can materially influence the reported embodied impacts.

The need for careful interpretation is reinforced by recent research. Burdett et al. (2026) assembled material-property and environmental data for emerging structural materials and reported that only 18% of the 204 emerging structural materials reviewed had embodied-carbon values and only 11% had embodied-energy values, demonstrating the limited availability of environmental data for newer materials. Their study also showed that material-level environmental information is valuable for screening but must be considered together with functional properties. Ranganath et al. (2024) demonstrated the importance of material-specific embodied-carbon data in a whole-building assessment, while Zhang et al. (2024) documented methodological inconsistencies across embodied-carbon assessment approaches. These findings indicate that the challenge is not simply to identify low-carbon materials, but to understand the provenance and comparability of the values assigned to them.

The present study is deliberately positioned as a material-level assessment rather than a comparative study of conventional and sustainable construction systems. Conventional materials are not treated as competing alternatives in the analysis. Instead, the study focuses on the reported embodied-energy and embodied-carbon characteristics of sustainable materials themselves and critically examines why published values vary.

1.1 Research gap

Three gaps motivate the present work. First, published values for sustainable and emerging materials are dispersed across databases and individual studies, making it difficult to obtain a consolidated view of their reported embodied-energy and embodied-carbon characteristics. Second, reported coefficients are often presented without sufficient attention to system boundary, geography, allocation, production route and carbon-accounting assumptions, creating a risk of false precision. Third, material categories such as fly ash, GGBS, recycled steel, bamboo, timber and earth-based materials are sometimes assigned a single representative value even though their environmental burdens can vary substantially with processing and supply-chain conditions.

A further gap concerns the relationship between embodied energy and embodied carbon. Treating energy as a proxy for carbon can be misleading where low-carbon electricity is used or where process emissions dominate. Similarly, assigning negative carbon values to bio-based materials without clearly separating fossil emissions, biogenic uptake, storage and end-of-life release can obscure the accounting basis.

1.2 Aim

The aim of this paper is to assess and quantify reported embodied-energy and embodied-carbon characteristics of selected sustainable construction materials and to critically examine the sources of variability and uncertainty in those values.

1.3 Objectives

1. To compile representative reported embodied-energy values for selected sustainable construction materials.
2. To compile representative reported embodied-carbon values and identify their dominant emission sources.
3. To examine how production route, processing intensity, energy source, transport and geographic context influence the reported values.
4. To critically evaluate allocation assumptions for industrial by-products and carbon-accounting conventions for recycled and bio-based materials.
5. To assess the consistency and limitations of available material-level data and identify requirements for future project-specific life cycle assessment.

1.4 Scope and contribution

The study is a secondary-data critical review and quantitative screening assessment. It does not claim to constitute a complete ISO 14040/14044 life cycle assessment, and it does not develop a building-level conventional-versus-sustainable comparison. Its contribution is the structured interpretation of material-level embodied-energy and embodied-carbon coefficients, with explicit attention to data provenance, boundary conditions, allocation and uncertainty. This positioning is intended to provide a methodological foundation for subsequent comparative assessment and full life cycle assessment studies.

2. Literature Review

2.1 Embodied energy and embodied carbon in construction materials

The Inventory of Carbon and Energy (ICE) has been an important reference for embodied-impact factors in construction materials. The original work by Hammond and Jones established a structured database of embodied energy and carbon factors, while later ICE versions developed under Circular Ecology focused increasingly on embodied carbon. The present manuscript uses the earlier source basis retained in the original study, but the current status of the database must be recognized: Circular Ecology reports that embodied-energy factors were no longer included in ICE from 2019 and that the current educational ICE resource is primarily an embodied-carbon dataset. Accordingly, older embodied-energy values should be treated as historical literature-derived factors rather than assumed to represent current universal product performance.

This distinction is important for the present paper. Embodied energy is less consistently reported in recent environmental product declarations and literature than global warming potential, while embodied-carbon datasets increasingly provide product- or region-specific information. Consequently, energy values may have greater uncertainty and weaker data availability than carbon values for emerging materials.

2.2 Recent evidence on emerging sustainable materials

Burdett et al. (2026) provide one of the most relevant recent demonstrations of the environmental-data gap for emerging structural materials. Their database included 409 materials and 21 material properties, while only a minority of emerging materials had published embodied-carbon or embodied-energy data. Their results demonstrate both the potential of emerging materials and the need to integrate environmental data with mechanical and functional properties.

Ranganath et al. (2024) evaluated a 265 m² end-terrace home in Michigan using whole-building life cycle assessment. Their analysis illustrates that material-specific contributions from concrete, steel and other products can dominate embodied carbon at building scale. The study is useful as evidence of the importance of material coefficients, but its building-specific results should not be transferred directly to other climates, construction systems or supply chains.

Long et al. (2024) examined embodied greenhouse-gas emissions of building materials in Shanghai and demonstrated the importance of both material intensity and material quantity. The relevance to the present study is that a low per-kilogram coefficient does not automatically imply a low building-level impact if the material is used in large quantities, while a higher-intensity material may contribute less when used sparingly.

Zhang et al. (2024), in the NIST systematic review, identified differences among process-based, input-output and hybrid approaches, as well as inconsistencies in boundaries, databases and reduction strategies. These methodological differences are central to the interpretation of the material-level values compiled in the present study.

2.3 Resource context

The wider resource context also supports the need for material-level assessment. The UNEP International Resource Panel's Global Resources Outlook 2024 reports that global material extraction has increased dramatically over recent decades and projects further growth without substantial changes in resource-use patterns. Construction is closely connected with this trend through demand for mineral, metal, biomass and manufactured materials. Embodied energy and carbon therefore represent important but not exhaustive indicators of material sustainability.

3. Research Methodology

3.1 Research design

The study adopts a secondary-data critical review design. Published embodied-energy and embodied-carbon coefficients are collated and organized by sustainable-material category. The analysis is not a statistical meta-analysis because the underlying studies differ in material definitions, functional units, system boundaries and geographic conditions. Instead, ranges reported in the source literature are retained where harmonization is insufficient, and the causes of variability are examined qualitatively and, where possible, through simple derived indicators.

3.2 Material selection

The material set was derived from the materials already identified in the source manuscript and grouped into five broad categories: low-carbon cementitious materials, recycled materials, earth-based materials, bio-based materials and engineered sustainable materials. Materials are considered sustainable in this paper when the literature identifies one or more potential sustainability attributes, including industrial by-product utilization, recycled feedstock, renewable feedstock, reduced processing intensity, reduced clinker content or potential circularity. The term does not imply superior performance across all environmental categories.

3.3 Data sources and provenance

The source manuscript compiled numerical values primarily from the ICE database and cited literature, with cross-checking against Burdett et al. (2026), Ranganath et al. (2024), Long et al. (2024), Zhang et al. (2024) and UNEP (2024). The present revision retains the numerical ranges available in the source manuscript but explicitly recognizes a provenance limitation: the original draft did not provide a source-by-source citation for every numerical row in Tables 1 and 2. Therefore, the ranges are treated as representative literature-synthesis values rather than as independently re-derived database values. Before final publisher submission, each numerical coefficient should be traced to its exact underlying source and version, particularly for ICE-derived values.

This qualification is especially important because Circular Ecology has subsequently updated the ICE resource. Circular Ecology states that ICE v3.0 was released in 2019, that embodied-energy factors were subsequently excluded from ICE, and that the current ICE educational resource is intended primarily for educational use. Therefore, the historical ICE version used to generate a particular value must be explicitly identified in any final data table or supplementary dataset.

3.4 System boundary

A cradle-to-gate material boundary is adopted as the principal reporting basis. It encompasses relevant raw-material extraction, processing and manufacturing stages up to the factory gate. Transport to the construction site, installation, use, maintenance and end-of-life stages are not included in the reported material coefficients unless explicitly stated in the underlying source. This boundary is selected to improve consistency at the material level, but it also limits direct interpretation of the values as whole-life building impacts.

The use of a cradle-to-gate boundary is consistent with the type of material-level screening commonly reported in embodied-carbon databases and recent material-property studies, but it should not be interpreted as a complete LCA. ISO 14040 and ISO 14044 provide the overarching principles and requirements for LCA; the present study uses selected LCA concepts for boundary description without claiming completion of all LCA phases.

3.5 Indicators and functional units

Embodied energy is reported in MJ/kg and embodied carbon in kgCO₂e/kg because these units are the dominant mass-normalized forms available in the source material. Mass-normalized values are useful for screening but do not establish functional equivalence between different construction materials. A kilogram of timber, concrete, steel, bamboo or earth material does not provide the same structural, thermal or service function. Consequently, the present paper avoids using the mass-normalized coefficients to claim that one material is universally preferable to another.

3.6 Data harmonization

The following metadata are considered essential for interpreting every coefficient: material definition, production route, system boundary, geographic context, energy mix, transport assumptions, moisture condition, allocation

method, carbon-accounting convention and data year. Where these attributes were not available in the source manuscript, the value is retained as reported but classified as subject to methodological uncertainty.

3.7 Quantitative treatment

Where a source provides only a minimum and maximum value, the present analysis reports the range rather than creating a false precision. A simple midpoint may be used only as a descriptive indicator:

$$\text{Midpoint} = (\text{Minimum} + \text{Maximum}) / 2$$

The relative spread of a reported range can also be expressed as:

$$\text{Relative spread (\%)} = [(\text{Maximum} - \text{Minimum}) / \text{Midpoint}] \times 100$$

These calculations describe the breadth of reported values; they do not represent statistical uncertainty unless the underlying observations are independently sampled. Standard deviation, coefficient of variation and formal meta-analysis were not calculated from range-only data because the source manuscript does not contain the individual observations needed for such statistics.

3.8 Critical assessment framework

- Production route and process intensity
- Energy source and electricity carbon intensity
- Geographical and supply-chain context
- Transportation and logistics
- Allocation of co-products and industrial by-products
- Recycled-content and avoided-burden assumptions
- Biogenic carbon uptake, storage and end-of-life treatment
- Data age, completeness and traceability

4. Sustainable Construction Materials Considered

The assessment concentrates on material classes that have been identified in the source manuscript as potential lower-impact or resource-efficient construction pathways. The objective is not to rank these classes but to establish the range of reported embodied-energy and embodied-carbon characteristics and identify the factors controlling those values.

Material category	Representative materials	Potential sustainability attribute
Low-carbon cementitious	Fly ash; GGBS; blended cement; LC3-type systems	Reduced clinker or industrial by-product utilization
Recycled materials	Recycled/EAF steel; recycled aggregate	Secondary feedstock and reduced virgin extraction
Earth-based	Compressed stabilised earth block; rammed earth	Low processing intensity; local mineral feedstock
Bio-based	Softwood timber; bamboo; cellulose/hemp-type materials	Renewable or bio-based feedstock; potential biogenic carbon storage
Engineered sustainable	CLT; glulam; other engineered timber products	Engineered structural performance with bio-based feedstock

The classification is functional for the purposes of the review and should not be interpreted as a certification of environmental superiority. A material can have low embodied carbon while presenting other environmental burdens, and a material with relatively high mass-normalized energy can still perform favorably on a functional basis.

5. Quantification of Embodied Energy

The source manuscript reports a broad range of embodied-energy values across construction materials. For the present Paper 1, the focus is restricted to interpreting the sustainable-material entries rather than comparing them against conventional alternatives.

Material	Reported embodied energy (MJ/kg)	Indicative descriptor*	range	Key controlling factors
Fly ash (by-product)	0.05–0.10	Low		Parent-process allocation; transport/processing
GGBS (by-product)	0.50–1.00	Low		Parent-process allocation; granulation/grinding
Ready-mix concrete (OPC, 1:2:4)	0.90–1.30	Contextual		Mix composition; cement content
Compressed stabilised earth block	0.40–0.80	Very low		Stabiliser content; soil processing
Rammed earth (in situ)	0.40–0.70	Very low		Soil preparation and compaction
Softwood timber (sawn)	7.40–10.00	Moderate on mass basis		Drying, processing and transport
Cross-laminated timber	8.50–11.00	Moderate on mass basis		Drying, lamination and adhesives
Bamboo (raw/treated)	0.50–3.00	Low to very low		Treatment, drying and transport

*The descriptors are used only to describe the ranges reported in the source manuscript and are not intended as universal performance rankings.

5.1 Interpretation of reported embodied-energy values

The reported values demonstrate that embodied energy is strongly associated with processing intensity, but the relationship is not purely material-specific. Industrial by-products such as fly ash and GGBS can receive very low burdens when the principal upstream energy requirement is assigned to the parent process. This does not mean that the physical processing of the by-product is energy-free. Grinding, drying, granulation, separation and transport may still require energy and should be included according to the selected system boundary.

Earth-based materials show low reported values in the source dataset because excavation, preparation and compaction can require substantially less thermal processing than kiln-fired products. However, the energy intensity of compressed earth block can increase with cement stabilization, mechanical processing and long-distance transport. The embodied-energy coefficient therefore depends on both the earth material and the manufacturing specification.

The reported values for bamboo and engineered timber illustrate why mass-normalized embodied energy must be interpreted carefully. Timber products may have higher MJ/kg values than some mineral materials because drying and processing require energy, even though their density and functional role differ. For engineered timber, adhesive use, drying energy, lamination and manufacturing efficiency can shift the result. Therefore, low energy per kilogram should not be treated as a sufficient criterion for material selection.

5.2 Drivers of embodied-energy variability

Production technology is a primary source of variability. Cementitious materials are influenced by kiln efficiency, clinker content and fuel use; metals are influenced by primary versus secondary production routes; timber and bamboo are influenced by drying, treatment and manufacturing; and earth materials are influenced by stabilization and mechanization.

Electricity mix is another important driver. Two facilities producing nominally identical products can have different embodied-energy and embodied-carbon profiles when their electricity sources differ. This issue is particularly relevant to electrically intensive processes such as metal recycling and engineered-material manufacturing.

Transport can be material to the result for low-density materials and regionally dispersed feedstocks. A low-processing material does not necessarily retain a low embodied impact when transported over large distances. The same issue applies to industrial by-products, whose sustainability benefit depends partly on whether they are available near the manufacturing location.

5.3 Interpretation of range breadth

The range widths reported in the source manuscript should themselves be treated as information. For example, bamboo is reported at 0.5–3.0 MJ/kg, giving a midpoint of 1.75 MJ/kg and a relative spread of approximately 143%. The range for rammed earth is 0.4–0.7 MJ/kg, with a midpoint of 0.55 MJ/kg and a relative spread of approximately 55%. These simple descriptors indicate that the literature variability for bamboo is substantially wider than that reported for rammed earth in the present dataset. They do not, however, quantify statistical uncertainty.

Similarly, fly ash is reported at 0.05–0.10 MJ/kg, giving a midpoint of 0.075 MJ/kg and a relative spread of approximately 67%. The breadth may reflect differences in processing and allocation rather than random measurement error. Such observations support the need to report metadata with every embodied-energy coefficient.

6. Quantification of Embodied Carbon

The source manuscript reports the following representative cradle-to-gate embodied-carbon values for sustainable materials. These values are retained as a literature-synthesis dataset and should not be interpreted as universal product coefficients.

Material	Reported embodied carbon (kgCO ₂ e/kg)	Dominant/important source
Steel (recycled/EAF route)	0.40–0.70	Electric-arc-furnace electricity; scrap processing
Fly ash (by-product)	0.004–0.020	Allocated transport/processing in the source dataset
GGBS (by-product)	0.020–0.080	Granulation and grinding; allocation basis
30% fly-ash blended concrete	0.07–0.11	Reduced clinker content
50% GGBS blended concrete	0.05–0.09	Reduced clinker content
Compressed stabilised earth block	0.02–0.08	Cement stabiliser and processing
Rammed earth (in situ)	0.02–0.06	Low processing; material and transport conditions
Softwood timber (excluding sequestration)	0.31–0.46	Harvesting, drying and transport
Reused/recycled structural steel	~0.05	Collection, testing and limited reprocessing

6.1 Cementitious materials and process emissions

Portland cement demonstrates why embodied energy and embodied carbon cannot be treated as interchangeable. Calcination of limestone releases carbon dioxide through the chemical conversion of calcium carbonate to calcium oxide. This process contribution occurs independently of the thermal efficiency of the kiln. Consequently, reducing clinker content through fly ash, GGBS or calcined-clay substitution can reduce embodied carbon substantially even when the corresponding reduction in total energy is smaller.

The source manuscript reports 30% fly-ash blended concrete at 0.07–0.11 kgCO₂e/kg and 50% GGBS blended concrete at 0.05–0.09 kgCO₂e/kg. These values should be interpreted as mixture-level coefficients rather than

universal factors because actual embodied carbon depends on cement content, supplementary-cementitious-material properties, water-to-binder ratio, aggregate composition, manufacturing electricity and transport.

6.2 Allocation of fly ash and GGBS

The very low carbon values assigned to fly ash and GGBS are particularly sensitive to allocation. When an industrial by-product receives little or none of the upstream burden of the parent process, its reported embodied carbon can be very low. Under alternative allocation procedures, its coefficient can increase. Therefore, the numerical value of a by-product is inseparable from the accounting rule used to derive it.

For future quantitative studies, at least three allocation perspectives should be considered where data permit: mass allocation, economic allocation and system expansion/avoided-burden approaches. The resulting spread should be reported as an accounting sensitivity rather than hidden within a single factor.

6.3 Recycled and reused materials

Recycled and reused steel illustrates the importance of production route. Primary steel is dominated by ore reduction and associated high-temperature processing, whereas recycled steel produced through an electric arc furnace is primarily dependent on scrap preparation and electricity. The carbon result therefore depends strongly on electricity carbon intensity, scrap availability, furnace efficiency and transport.

Reused steel requires a different accounting perspective from recycled steel. Reuse can avoid a substantial amount of reprocessing, but the burden assigned to inspection, testing, cleaning, transportation and adaptation depends on the system boundary. The two pathways should therefore not be treated as interchangeable.

6.4 Earth-based materials

The reported embodied-carbon values for compressed stabilised earth block and rammed earth are low in the source dataset, but their performance depends strongly on stabilization, moisture condition, transport and construction method. Cement stabilization can materially increase the carbon coefficient of earth blocks. Mechanized production and long-distance transportation can also erode the benefit associated with local soil.

6.5 Bio-based materials and biogenic carbon

The source manuscript reports softwood timber at 0.31–0.46 kgCO₂e/kg when sequestration is excluded. This distinction is methodologically important. Fossil greenhouse-gas emissions associated with harvesting, drying, processing and transport should be reported separately from biogenic carbon uptake and storage. A negative net value should not be assigned automatically to timber or bamboo without specifying the carbon-accounting framework, forest-management assumptions, storage period, land-use change and end-of-life treatment.

For engineered timber, adhesives and energy-intensive drying and processing must also be considered. Therefore, bio-based feedstock alone does not determine the embodied-carbon result. The appropriate interpretation is that bio-based materials introduce an additional carbon-accounting dimension that must be reported transparently.

7. Critical Analysis of Reported Values

7.1 Variability is a material characteristic and a data characteristic

The ranges compiled in this study represent two forms of variability. The first is genuine physical variability among products produced under different conditions. The second is methodological variability caused by differences in boundaries, allocation, databases and accounting conventions. These two forms should not be conflated. A wide literature range does not necessarily mean that measurements are imprecise; it may mean that the studies are evaluating different products or processes.

7.2 System-boundary effects

Cradle-to-gate values are useful for material screening, but they exclude transport beyond the factory gate, construction activities, use-stage replacement and end-of-life processes. For low-processing materials, transport may be a relatively important share of the total. For durable materials with long service lives, end-of-life recovery may materially affect whole-life results. Consequently, a cradle-to-gate coefficient should be labeled explicitly and should not be presented as a complete life-cycle impact.

7.3 Geographic context

Geographic context affects both energy and carbon. Electricity carbon intensity, fuel availability, production technology, transport distance, feedstock sourcing and waste-management infrastructure vary between countries and regions. A factor derived from one national supply chain should therefore not automatically be transferred to another region. This is particularly relevant to Indian construction, where cement, steel, brick, fly ash, GGBS and biomass supply chains may differ from those represented in UK, European or North American databases.

7.4 Energy–carbon relationship

The compiled data support the conclusion that embodied energy and embodied carbon should be treated as related but distinct indicators. Carbon depends on the carbon intensity of energy and on non-energy process emissions. Cement is the clearest example because calcination contributes substantially to its greenhouse-gas footprint. Conversely, an electrically intensive process can have a lower carbon footprint when supplied by a low-carbon electricity system. Therefore, reducing embodied energy does not necessarily produce a proportional reduction in embodied carbon.

A formal correlation coefficient is not calculated in this study because the available information consists primarily of literature ranges rather than matched individual observations with consistent material definitions and boundaries. Computing a correlation from the range endpoints would create spurious precision. A future harmonized database containing source-level observations should be used for regression or correlation analysis.

7.5 Allocation sensitivity

Allocation is one of the most consequential methodological choices for industrial by-products. The apparent environmental advantage of fly ash and GGBS is partly created by the allocation of upstream burdens to the parent industrial process. Alternative allocation approaches can therefore change the coefficient substantially. The same principle applies to recycled materials, where avoided virgin production may be credited under one method but not another.

7.6 Data quality and traceability

The data quality issue is especially important for emerging materials. Burdett et al. (2026) found that only 18% of the emerging structural materials in their review had embodied-carbon values and only 11% had embodied-energy values. The present review reaches a compatible methodological conclusion: environmental claims for emerging materials are often constrained by missing or inconsistent data rather than by a lack of promising material technologies.

A publishable material-level dataset should therefore report, for each coefficient, the source, database version, publication year, geography, functional unit, system boundary, production route, allocation method and whether biogenic carbon is included. Without these metadata, numerical values are difficult to reproduce or transfer.

7.7 Quantified range indicators

Material	Reported range	Midpoint	Relative spread	Interpretation
Bamboo	0.5–3.0 MJ/kg	1.75	143%	Wide reported variability; processing/treatment likely important
Rammed earth	0.4–0.7 MJ/kg	0.55	55%	Relatively narrower range in source synthesis
Fly ash	0.05–0.10 MJ/kg	0.075	67%	Allocation and processing assumptions important
CSEB	0.4–0.8 MJ/kg	0.60	67%	Stabilizer and production method important
Softwood timber	0.31–0.46	0.385	39%	Fossil emissions

	kgCO ₂ e/kg			only in source definition
--	------------------------	--	--	---------------------------

The relative-spread calculation is a descriptive screening metric and should not be interpreted as a coefficient of variation. It demonstrates why reporting only a single representative number can conceal substantial literature variability.

8. Broader Environmental Considerations

Embodied energy and carbon are the principal quantitative indicators examined in this paper. Other environmental dimensions are discussed only as contextual considerations because the source manuscript does not contain sufficiently harmonized inventories to calculate them consistently.

Environmental dimension	Critical observation	Limitation
Water use	Processing, cooling, curing and washing can be important; low-processing earth materials may require less process water, but site-specific conditions matter.	Requires consistent process-water and supply-chain inventories.
Resource depletion	Virgin mineral and metal extraction can create substantial resource pressures; recycled and by-product pathways may reduce demand for primary feedstocks.	Requires a defined resource-depletion method.
Waste and circularity	Recycled and reusable materials can reduce waste flows, while earth and some timber products may have favorable recovery pathways under suitable conditions.	End-of-life assumptions strongly influence results.
Land use and biodiversity	Bio-based materials depend on land management and sourcing; mineral extraction also has land impacts.	Requires land-use-change and biodiversity indicators.
Air emissions	Manufacturing routes can generate particulate matter, NO _x , SO _x and other pollutants in addition to greenhouse gases.	Requires quantitative inventory or LCIA.
End-of-life	Reuse, recycling, downcycling, landfill and biological degradation can change whole-life impacts.	Not quantified in the present cradle-to-gate study.

The purpose of this section is to prevent overinterpretation of embodied-carbon performance as a complete sustainability assessment. A material can perform well on embodied carbon while presenting other burdens. Conversely, a material with a higher mass-normalized energy coefficient may have favorable performance when assessed per functional unit. Full multi-impact assessment is therefore reserved for subsequent life cycle assessment work.

9. Implications for Material-Level Assessment

9.1 Need for harmonized reporting

Every published embodied-energy or embodied-carbon coefficient should be accompanied by a minimum metadata set: material specification, production route, system boundary, geography, data year, energy mix, transport assumptions, allocation method and carbon-accounting convention. This would make future databases more useful and reduce inappropriate transfer of values between contexts.

9.2 Need for product-specific environmental data

Generic database factors are useful during early-stage screening, but project-level decisions should progressively move toward product-specific environmental product declarations or equivalent verified datasets. The recent evidence from Burdett et al. (2026) shows that emerging materials are particularly affected by data scarcity.

9.3 Relevance to Indian construction

For Indian construction, regionalized embodied-impact factors are particularly important because production technologies, electricity mix, transport distances, availability of fly ash and GGBS, brick manufacturing practices, recycled-material infrastructure and biomass supply chains differ from those represented in international datasets. A regional database should therefore distinguish Indian production routes and energy conditions rather than importing foreign coefficients without adjustment.

9.4 Implications for future LCA

The present material-level assessment should be regarded as a screening stage preceding project-specific LCA. Future work should define a functional unit, establish a complete life-cycle inventory, include transport and construction where relevant, quantify use and end-of-life stages where appropriate, evaluate multiple environmental impact categories and conduct sensitivity and uncertainty analyses. This progression will allow the material-level findings of the present paper to be tested at building scale without conflating screening coefficients with whole-life results.

10. Limitations

- The study is based on secondary data and does not include laboratory measurements or primary industrial inventories.
- The numerical ranges retained from the source manuscript are representative literature-synthesis values; exact source-level mapping for every numerical row was not available in the original draft and must be verified against the underlying publications or database version before final submission.
- The material-level functional unit is mass-based because that is the most consistently reported unit in the source material. This does not establish functional equivalence between materials.
- System boundaries differ across the underlying literature even where authors use similar terminology; this creates residual methodological heterogeneity.
- Embodied energy is less consistently updated in recent databases than embodied carbon, so some energy factors may be older than the carbon factors.
- Biogenic carbon, allocation and recycled-content accounting can materially alter reported results and cannot be resolved without source-specific methodological information.
- The study does not quantify a full set of environmental impact categories and therefore should not be interpreted as a complete sustainability ranking.

11. Future Research Directions

6. Develop a source-level database containing individual observations rather than only literature ranges.
7. Standardize system boundaries and metadata before statistical pooling.
8. Develop India-specific embodied-energy and embodied-carbon coefficients for major sustainable material pathways.
9. Perform allocation sensitivity analysis for fly ash, GGBS and other industrial by-products.
10. Separate fossil, biogenic and stored carbon for bio-based materials and track end-of-life release or recovery.

11. Evaluate sustainable materials using functional units such as per m³ of material, per m² of wall/floor assembly, or per unit of structural/thermal service rather than relying solely on kg-based factors.
12. Extend the material-level assessment to full LCA and multi-impact LCIA in a subsequent study.
13. Develop uncertainty propagation or Monte Carlo analysis once source-level observations are available.
14. Integrate material environmental data with mechanical and durability properties to support multi-criteria sustainable material selection.

12. Conclusions

This critical review assessed and quantified reported embodied-energy and embodied-carbon characteristics of selected sustainable construction materials, with emphasis on low-carbon cementitious materials, recycled materials, earth-based materials, bio-based materials and engineered sustainable products. The analysis demonstrates that the environmental characteristics of sustainable materials cannot be represented reliably by a single universal coefficient.

The reported embodied-energy values in the source dataset span wide ranges, with particularly low values reported for industrial by-products and minimally processed earth materials. However, these low values are strongly influenced by allocation and processing assumptions. Bio-based and engineered products show that mass-normalized energy values must be interpreted together with manufacturing intensity, moisture condition, functional performance and supply-chain context.

Embodied carbon similarly varies with material composition and production route, but its relationship with embodied energy is not one-to-one. Cementitious materials illustrate the importance of process emissions from calcination, while recycled metals illustrate the role of electricity carbon intensity. For fly ash and GGBS, the reported low coefficients are strongly dependent on how the upstream burden of the parent process is allocated. For timber and other bio-based materials, fossil emissions and biogenic carbon storage must be reported separately and transparently.

The critical analysis further shows that variability in published coefficients arises from both physical production differences and methodological differences. System boundary, geography, electricity mix, transportation, allocation, recycling assumptions and carbon-accounting conventions can all influence the reported value. Consequently, material-level screening should use ranges and metadata rather than relying on a single number without qualification.

The principal contribution of the study is therefore methodological as well as quantitative: it establishes a structured basis for assessing embodied energy and carbon in sustainable construction materials while identifying the conditions required for meaningful interpretation. The findings support the development of harmonized, region-specific and source-traceable material databases. They also provide a foundation for the next stage of research, in which the quantified material coefficients can be incorporated into functional, building-scale and full life cycle assessment frameworks.

References

- [1] Burdett, S., Arora, M., & Myers, R. J. (2026). Sustainable materials selection with emerging structural materials. *npj Materials Sustainability*, 4, Article 13. <https://doi.org/10.1038/s44296-026-00099-7>
- [2] Hammond, G., & Jones, C. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers – Energy*, 161(2), 87–98.
- [3] Hammond, G., & Jones, C. (2019). *Inventory of Carbon and Energy (ICE) Database, Version 3.0*. University of Bath / Circular Ecology.
- [4] International Organization for Standardization. (2006). *ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework*. Geneva: ISO.
- [5] International Organization for Standardization. (2006). *ISO 14044:2006. Environmental management — Life cycle assessment — Requirements and guidelines*. Geneva: ISO.
- [6] Long, Y., Cui, H., Lu, Z., Huang, B., Wang, X., & Dou, Y. (2024). Prediction of embodied GHG emissions of building materials in Shanghai. *Carbon Footprints*, 3, Article 12. <https://doi.org/10.20517/cf.2024.12>
- [7] Ranganath, S., McCord, S., & Sick, V. (2024). Assessing the maturity of alternative construction materials and their potential impact on embodied carbon for single-family homes in the American Midwest. *Frontiers in Built Environment*, 10, 1384191. <https://doi.org/10.3389/fbuil.2024.1384191>

- [8] United Nations Environment Programme, International Resource Panel. (2024). Global Resources Outlook 2024: Bend the Trend — Pathways to a Liveable Planet as Resource Use Spikes. Nairobi: UNEP.
- [9] Zhang, Y., Sattar, S., Cook, D. T., Johnson, K. J., & Fung, J. F. (2024). Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles. NIST Special Publication 1324. National Institute of Standards and Technology. <https://doi.org/10.6028/NIST.SP.1324>