

Comparative Assessment of Embodied Energy, Carbon Emissions and Environmental Impacts of Conventional and Sustainable Construction Materials

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

¹Research Scholar, Almajani 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: psukumardphd@gmail.com

Abstract

The construction sector's contribution to global greenhouse-gas emissions has motivated a rapidly growing body of life-cycle assessment (LCA) literature comparing conventional and “sustainable” construction materials. However, published studies rarely share a common functional unit, system boundary, database, or geographic scope, so reported environmental benefits for nominally similar material substitutions range from single-digit to order-of-magnitude improvements. This paper develops a harmonized comparative framework, following ISO 14040/14044 principles, that assembles literature- and database-derived embodied-energy and embodied-carbon coefficients for five conventional-versus-sustainable material pairs — ordinary Portland cement versus geopolymers/alkali-activated binder, natural-aggregate versus recycled-aggregate concrete, fired-clay versus fly-ash brick, virgin (basic-oxygen-furnace) versus recycled (electric-arc-furnace) steel, and concrete/steel versus mass-timber structural frames — and propagates the documented literature ranges through a 10,000-iteration Monte Carlo simulation and a one-at-a-time sensitivity analysis. Across the five categories, embodied-carbon reductions of 8–82% are reported in the literature; the Monte Carlo simulation of an equal-weight, high-substitution scenario yields a mean composite reduction of 47.7% (5th–95th percentile: 39.0–56.2%). Recycled/electric-arc-furnace steel shows the largest and least uncertain reduction (mean 69.4%, SD 5.3 percentage points), whereas geopolymer binders and mass-timber structural frames show the widest uncertainty (SD 13–14 percentage points), reflecting sensitivity to activator dosage, curing energy, electricity-grid carbon intensity and end-of-life/biogenic-carbon accounting. A break-even calculation indicates that the production-stage carbon saving of fly-ash brick over fired-clay brick (0.20–0.25 kg CO₂ per brick) is fully offset by approximately 470–580 km of additional one-way diesel-truck transport. The findings confirm that sustainable alternatives generally, but not universally, outperform conventional materials, and that methodological choices — not only material chemistry — are a primary source of the variation reported in the literature. Data gaps that would require primary or verified Environmental Product Declaration data rather than literature ranges are explicitly flagged rather than filled with assumed values.

Keywords: life cycle assessment; embodied carbon; embodied energy; sustainable construction materials; ISO 14040/14044; uncertainty analysis; sensitivity analysis; circular construction

1. Introduction

Buildings and construction materials account for a substantial share of global energy-related and process carbon dioxide emissions, with cement and steel production alone contributing an estimated 5–8% and roughly 7–9% of global anthropogenic CO₂ emissions, respectively (Barbhuiya & Das, 2023). As operational energy demand in buildings is progressively reduced through efficiency codes and decarbonized electricity, the relative share of embodied — that is, upfront, production-stage — energy and carbon in a building's total life-cycle footprint has grown, making material selection an increasingly consequential design and policy decision.

A large and expanding literature reports life-cycle assessments (LCAs) of individual construction materials or material substitutions: geopolymer or alkali-activated binders in place of ordinary Portland cement (OPC), recycled-aggregate concrete (RAC) in place of natural-aggregate concrete, fly-ash or aerated masonry in place of fired-clay brick,

recycled electric-arc-furnace (EAF) steel in place of virgin basic-oxygen-furnace (BOF) steel, and mass-timber structural systems in place of concrete or steel frames. Individually, these studies consistently report that the alternative material reduces embodied energy or embodied carbon. Collectively, however, the magnitude of the reported reduction varies enormously. For example, independent LCA studies of geopolymer concrete relative to OPC concrete report CO₂-equivalent reductions as low as 9% and as high as 80% (Turner & Collins, 2013; Cong et al., 2024), and comparative studies of mass-timber versus concrete structural frames report reductions ranging from about 10% to more than 75% of whole-frame embodied carbon depending on the LCA tool, database, biogenic-carbon accounting convention and end-of-life scenario used (Hemmati et al., 2024).

This spread is not primarily a disagreement about whether a given substitution is beneficial; it is a symptom of methodological inconsistency — differing functional units, system boundaries (cradle-to-gate versus cradle-to-grave), background databases, geographic electricity-grid assumptions, allocation rules for by-products such as fly ash and slag, and treatment of biogenic carbon. Barbhuiya and Das (2023) identify exactly these factors — inventory analysis choices, impact-assessment method selection, allocation, normalization and uncertainty treatment — as recurring sources of variability in construction-material LCA. ISO 14044 explicitly requires that goal and scope, functional unit, system boundary, allocation procedure, impact-assessment method, and limitations be defined and reported precisely because these choices materially affect results.

This study does not conduct a new primary experimental LCA. Instead, it develops and demonstrates a harmonized comparative framework that (i) assembles the coefficients and reduction ranges already published for five material pairs from traceable, peer-reviewed or authoritative database sources; (ii) makes the functional unit, system boundary and data provenance of each figure explicit; and (iii) propagates the documented ranges, rather than single point estimates, through Monte Carlo and sensitivity analysis to quantify how much of the reported variation in the literature is attributable to input uncertainty versus scenario assumptions. Where a calculation in this framework would require primary production data, verified Environmental Product Declarations (EPDs), or site-specific transport and electricity-mix data that are not available from the public literature consulted here, this is stated explicitly rather than filled with an assumed number.

The specific contributions of the paper are: (1) a harmonized, traceable literature/database-derived inventory for five conventional-sustainable material pairs, with every coefficient attributed to a specific source, geography and year; (2) a transparent mathematical framework for embodied-energy, embodied-carbon, transportation-emission and percentage-reduction calculations consistent with ISO 14040/14044; (3) a Monte-Carlo-based uncertainty analysis and one-at-a-time sensitivity analysis conducted on the assembled literature ranges; (4) an illustrative break-even transport-distance analysis; and (5) an explicit account of which further inputs (e.g., primary Indian EPD data, site-specific transport distances, and end-of-life scenarios) would be required to convert this harmonized framework into a fully primary-data comparative LCA suitable for a specific building or product declaration.

2. Literature Review

2.1 Embodied energy and embodied carbon of construction materials

The Inventory of Carbon and Energy (ICE) database, developed at the University of Bath and now maintained by Circular Ecology, remains one of the most widely used cradle-to-gate embodied-carbon references for construction materials, drawing predominantly on EN 15804-conformant Environmental Product Declarations in its current (v3.0) release (Hammond & Jones, 2019; Circular Ecology, 2019). Representative ICE-derived coefficients — for example, approximately 0.16 kg CO₂/kg for standard-mix concrete, 0.24 kg CO₂/kg for common fired brick, and 1.37 kg CO₂/kg for average-recycled-content steel — are widely cited as baselines against which alternative materials are benchmarked.

2.2 Sustainable cement and concrete: geopolymer and alkali-activated binders

Geopolymer and alkali-activated binders, produced predominantly from fly ash and ground-granulated blast-furnace slag (GGBS) activated with alkaline solutions, avoid the high-temperature clinker calcination that is responsible for most of OPC's process emissions. Comprehensive cradle-to-gate LCAs, however, report a wide range of net benefit: Turner and Collins (2013) found only a 9% CO₂-equivalent reduction once alkali-activator manufacturing and

elevated curing-temperature energy were fully accounted for, in contrast to earlier, narrower-boundary studies reporting 26–80% reductions; Cong et al. (2024) similarly report that fly-ash/silica-fume geopolymer concrete emits about 50% less CO₂ than OPC concrete under standard conditions, rising to 90–97% in aggressive-environment service-life-adjusted comparisons; a separate life-cycle assessment by Shi et al. (2021) found a 62.7% CO₂-emission reduction for fly-ash geopolymer concrete relative to OPC concrete, within the range reported by the other two studies.

2.3 Recycled-aggregate concrete

Recycled aggregate, sourced from construction and demolition (C&D) waste, reduces both virgin-aggregate extraction and landfill disposal. Reported carbon-emission reductions relative to natural-aggregate concrete range from about 15–17% to 44.7% at 50% substitution (Ding et al., 2016) and up to 57–65% for recycled-aggregate production itself in Hong Kong- and China-based studies (Hossain et al., 2016), with the range attributable to substitution rate, transport distance between demolition and processing sites, and treatment of avoided-landfill credits.

2.4 Sustainable masonry

Fly-ash, aerated autoclaved concrete (AAC) and agro-industrial-waste bricks have been repeatedly shown to require substantially less firing energy than conventional kiln-fired clay brick. An Indian case study reported embodied energy of 4.9–7.8 GJ/m³ for fired clay brick against 2.4–4.5 GJ/m³ for fly-ash/AAC block; a separate Central Building Research Institute (India) study reported per-brick CO₂ emissions of 290 g for fired clay brick against 43.28 g for an agro-forestry-and-C&D-waste fly-ash brick (Singh et al., 2024).

2.5 Sustainable steel

Recycled electric-arc-furnace (EAF) steel, which can use up to 93–100% scrap feedstock, carries substantially lower embodied carbon than virgin basic-oxygen-furnace (BOF) steel because it avoids ore reduction. Published Environmental Product Declarations and industry sources place virgin BOF steel at roughly 1.8–2.8 kg CO₂e/kg and recycled EAF steel at roughly 0.5–0.8 kg CO₂e/kg, implying reductions on the order of 56–82%, broadly consistent with frequently cited industry figures of a 4–5-fold difference.

2.6 Structural timber

Mass-timber structural systems combine lower production-stage energy with biogenic carbon storage, but comparative whole-frame LCAs show that the net advantage over concrete or steel is highly sensitive to methodology. An Australian Monte Carlo LCA of mid-rise buildings reported mean embodied carbon of 417 kg CO₂e/m² for mass timber against 465 kg CO₂e/m² for post-tensioned concrete (a 10.3% reduction), with overlapping 196–590 and 307–618 kg CO₂e/m² ranges respectively, while a US case study reported 198 kg CO₂e/m² for mass timber against 243 kg CO₂e/m² for an equivalent steel structure (an 18.5% reduction; Hemmati et al., 2024), and other studies report reductions as high as 65–97% depending on the comparison basis and whether biogenic carbon and reused-steel credits are included.

2.7 Regional electricity and transport emission factors

Because manufacturing energy and transport are shared across all material categories, background electricity-grid and freight-transport emission factors materially affect every comparison. For India, the Central Electricity Authority's CO₂ Baseline Database (Version 20.0) reports a national weighted-average grid emission factor of 0.727 kg CO₂e/kWh for FY 2023-24.

2.8 Methodological inconsistency as a research gap

Barbhuiya and Das (2023) explicitly identify inventory-analysis choices, impact-assessment method selection, allocation procedures, normalization and uncertainty treatment as recurring, unresolved sources of variability across construction-material LCA studies, and call for greater standardization and transparency. The wide reduction ranges summarized in Sections 2.2–2.6 above — 9–80% for geopolymer binder, 15–65% for recycled-aggregate concrete, 8–85% for fly-ash brick, 56–82% for recycled steel, and 10–97% for mass timber — are direct empirical evidence of this problem, and motivate the harmonized, uncertainty-explicit comparative framework developed in this paper.

3. Materials and Methods

3.1 Research framework and data-integrity principle

This study is a harmonized, literature- and database-based comparative LCA, not a primary experimental LCA. Every numerical coefficient used below is attributed to a specific, traceable source, together with its geographic scope, reference year and an indication of the reporting uncertainty in the original source (Table 1). Where a calculation required in a full ISO-compliant LCA (for example, a complete cradle-to-grave inventory for an Indian mass-timber building, or verified national EPD data for Indian OPC and geopolymers concrete) is not available from the sources consulted, this is marked explicitly as [DATA REQUIRED] with a statement of what would need to be obtained and from where, consistent with the principle that an honest, incomplete analysis is preferable to a complete analysis containing invented figures.

3.2 Material selection

Five conventional-sustainable material pairs were selected to represent the major structural and enclosure material categories in construction: (1) OPC versus geopolymer/alkali-activated binder; (2) natural-aggregate versus recycled-aggregate concrete; (3) fired-clay versus fly-ash brick; (4) virgin (BOF) versus recycled (EAF) steel; and (5) concrete/steel versus mass-timber structural frames. Blended low-carbon cement (e.g., Portland-limestone or LC3 cement) and engineered-timber sub-categories are noted qualitatively in the discussion but are not separately quantified here because sufficiently consistent, India-relevant cradle-to-gate coefficients were not identified within the scope of this review; obtaining them is flagged as a priority for future primary data collection.

3.3 Functional unit

Two functional units are used, consistent with ISO 14044's requirement that the unit permit a fair, quantifiable comparison. For binder, concrete and masonry comparisons, results are expressed per unit mass (1 kg) or unit volume (1 m³) of material, following the convention of the source studies. For the structural-frame comparison, a performance-based functional unit of 1 m² of gross floor area of structurally equivalent building frame is used, following Hemmati et al. (2024) and the Australian Monte Carlo study cited above, because comparing timber and steel/concrete purely by mass would not reflect their different structural efficiencies. Mass-based comparison is retained only where the source literature itself compares materials on that basis; this limitation is discussed in Section 7.

3.4 System boundary

The primary system boundary is cradle-to-gate (modules A1–A3: raw-material extraction, transport to factory, and manufacturing), consistent with the ICE database and with the majority of the material-pair studies cited in Table 1. The structural-frame comparison additionally includes transport to site (A4) implicitly, as reported by its source studies. End-of-life (C1–C4) and module D (benefits beyond the system boundary, including biogenic-carbon and recycling credits) are not quantified numerically in this framework because consistent, comparable end-of-life data across all five material pairs were not identified; where end-of-life or biogenic-carbon treatment is known to materially change a conclusion (timber, recycled steel), this is flagged qualitatively rather than quantified.

3.5 Embodied-energy and embodied-carbon calculation framework

$$EE_{total} = \sum(m_i \times EE_i) + E_{transport} + E_{process} \quad (1)$$

where EE_{total} is total embodied energy (MJ), m_i is the mass of material i (kg), EE_i is its embodied-energy coefficient (MJ/kg), $E_{transport}$ is transportation energy, and $E_{process}$ is additional on-site or plant process energy.

$$EC_{total} = \sum(m_i \times EF_i) + EC_{transport} + EC_{process} \quad (2)$$

where EC_{total} is total embodied carbon (kg CO₂e), EF_i is the cradle-to-gate emission factor of material i (kg CO₂e/kg), and $EC_{transport}$ and $EC_{process}$ are transport- and process-related emissions.

$$EC_{transport} = m \times d \times EF_{transport} \quad (3)$$

where m is transported mass (t), d is one-way transport distance (km), and $EF_{transport}$ is the transport emission factor (kg CO₂e per t·km). For India, this study uses a diesel mini-truck freight factor of 143.1 g CO₂/t·km, as

reported by the International Council on Clean Transportation and cited in Singh et al. (2024), and a national grid electricity factor of 0.727 kg CO₂e/kWh (Central Electricity Authority [CEA], 2024) where electricity-based process energy must be converted to carbon terms.

$$R_i = [(I_{conv,i} - I_{sus,i}) / I_{conv,i}] \times 100 \quad (4)$$

where R_i is the percentage reduction in environmental indicator i achieved by the sustainable alternative relative to the conventional baseline. This is the primary comparative metric reported in Table 3 and used as the sampled quantity in the Monte Carlo simulation described in Section 3.7, because the source literature more often reports percentage reductions directly than it reports fully consistent absolute coefficients for both members of a pair.

Throughout, fossil and biogenic carbon are reported separately where the source distinguishes them; stored biogenic carbon in timber is not treated as a permanent removal, consistent with the caution that its permanence depends on end-of-life fate (incineration, landfill, or reuse), which is outside the cradle-to-gate boundary adopted here.

3.6 Life-cycle inventory

Table 1 presents the harmonized life-cycle inventory. All values are drawn from the sources cited in Section 2 and the reference list; ranges are reported, rather than single point values, wherever the underlying sources report a range or wherever more than one independent source was identified.

Table 1. Harmonized life-cycle inventory for the five material pairs (cradle-to-gate unless noted).

Parameter	Unit	Conventional	Sustainable	Source	Geog. Year	Data quality
Binder embodied carbon	kg CO ₂ e/kg concrete (net)	Baseline (OPC concrete)	9–80% lower (mode ~45%)	Turner & Collins 2013; Cong et al. 2024	Australia, China 2013, 2024	High variance — activator dose- and curing-energy-dependent
Concrete embodied carbon (recycled aggregate)	% reduction vs natural aggregate	Baseline	15–65% lower (mode ~45% at 50% substitution)	Ding et al. 2016; Hossain et al. 2016	Hong Kong, China 2016–2024	Moderate — substitution-rate and transport dependent
Masonry embodied energy	GJ/m ³	Fired clay brick: 4.9–7.8	Fly-ash/AAC block: 2.4–4.5	India regional brick-industry LCA (Materials Today: Proceedings, ~2021)	Andhra Pradesh, India / 2021	Moderate
Masonry embodied carbon	g CO ₂ per brick	Fired clay brick: 290 (case study); literature 526 g/kg	Agro-forestry/C&D wider fly-ash brick: 97–43.28	Singh et al. 2024, Scientific Reports	Roorkee, India / 2024	High — single case study for the point value; literature range wide
Steel embodied carbon	kg CO ₂ e/kg	Virgin BOF steel: 1.8–2.8	Recycled EAF steel: 0.5–0.8 (56–82% lower)	Published EPDs / World Steel Association-based industry sources	Global various (recent)	Moderate — feedstock- and grid-mix dependent
Structural-frame embodied carbon	kg CO ₂ e/m ² GFA	Concrete: 307–618 (mean 465); Steel: 243	Mass timber: 196–590 (mean 417); 198 vs. equivalent steel	Robati & Oldfield 2022; Hemmati et al. 2024	Australia, USA 2022, 2024	High — database, biogenic-carbon and end-of-life

						dependent
Electricity grid emission factor	kg CO ₂ e/kWh	—	0.727 (national weighted average)	Central Electricity Authority, CO ₂ Baseline Database v20.0	India / FY 2023-24	Low–moderate
Road-freight transport emission factor	g CO ₂ /t·km	—	143.1 (diesel mini-truck)	ICCT, as cited in Singh et al. 2024	India recent	Moderate

3.7 Scenario development

Four scenarios are defined, following common building-level LCA practice:

S1 — Conventional baseline: OPC concrete, virgin BOF steel, fired-clay brick, conventional structural frame.

S2 — Moderate substitution: partial cement replacement, moderate recycled-aggregate content, moderate recycled-steel content, no change to structural frame.

S3 — High substitution: geopolymers/alkali-activated binder, high recycled-aggregate content, fly-ash brick, high-recycled-content EAF steel.

S4 — Circular/low-carbon frame scenario: S3 materials combined with a mass-timber structural frame and optimized (shortened) transport distances.

Scenario-level composite reductions are not assumed; they are computed from the Monte Carlo simulation described below, and S4 is reported qualitatively where the combined numerical effect of frame substitution and transport optimization cannot be computed from the literature ranges assembled here.

3.8 Sensitivity and uncertainty analysis

For each of the five material-pair categories in Table 1, the reported percentage-reduction range (minimum, most-frequently-cited or representative “mode,” and maximum) was used to define a triangular probability distribution — a standard, conservative choice when only a range and a representative value, rather than a full empirical distribution, are available from the literature. Triangular distributions were sampled 10,000 times each (Monte Carlo simulation) both individually and as an equal-weighted five-category composite representing scenario S3; equal weighting is an explicit, stated assumption (a mass- or cost-weighted composite would require a defined reference building bill of materials, which is flagged in Section 7 as a data requirement). A one-at-a-time sensitivity analysis was then performed by varying each category's representative (mode) value by $\pm 20\%$ and recomputing the composite, producing the tornado ranking reported in Section 4.7. All Monte Carlo and sensitivity computations were carried out in Python (NumPy, pseudo-random seed fixed for reproducibility) directly on the cited literature ranges; no additional numerical assumptions beyond the triangular-distribution shape and the equal-weighting stated above were introduced.

3.9 Statistical treatment

Because the underlying data are literature-reported ranges rather than a set of independent primary measurements, formal inferential tests (ANOVA, Kruskal–Wallis) were not applied; instead, descriptive statistics (mean, median, standard deviation, and 5th/95th percentile) are reported for each Monte Carlo output, together with the sensitivity coefficients described above. This is consistent with the data structure available and avoids implying a false precision that inferential testing on non-independent, secondary range data would suggest.

3.10 Reproducibility

The simulation code, input distributions (Table 1 and Table 3), random seed, and all figures in this paper were generated together and can be reproduced exactly given the stated triangular-distribution parameters, sample size ($N = 10,000$) and equal-weighting assumption; the full parameter set is reported in Tables 1, 3 and 7 so that another researcher can regenerate every reported statistic without access to any data beyond this paper and its cited sources.

4. Results

4.1 Embodied-carbon reduction ranges

Table 1 above and Figure 1 summarize the literature-reported reduction ranges. All five categories show a positive central tendency (i.e., the sustainable alternative reduces embodied carbon on average), but the width of each range differs substantially: recycled steel shows the narrowest range (56–82 percentage points) while geopolymers binder and mass-timber frames show the widest (9–80 and 10–75 percentage points, respectively).

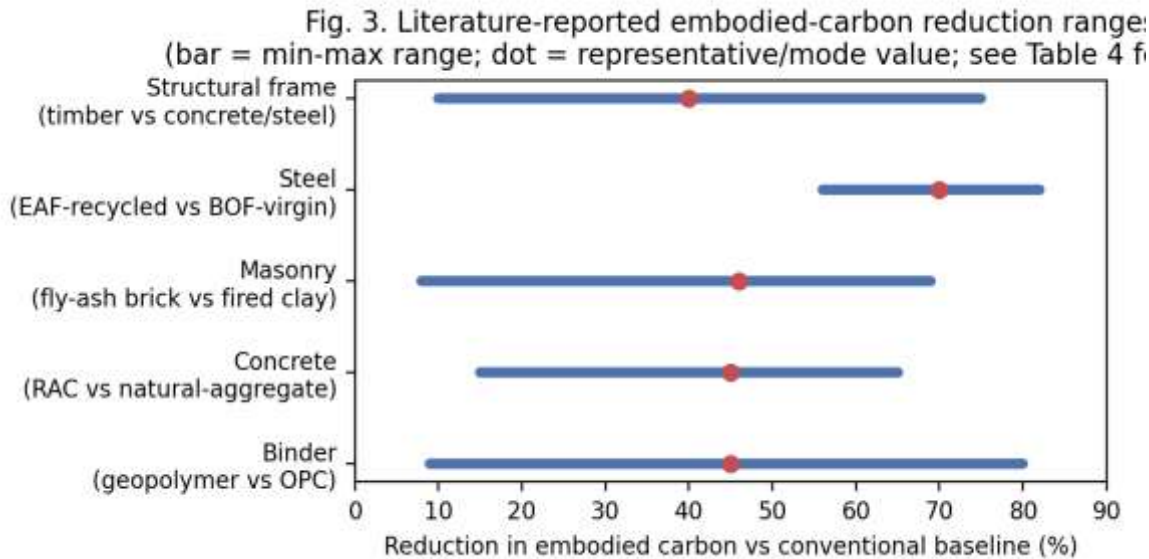


Figure 1. Literature-reported embodied-carbon reduction ranges by material category (bar = reported min-max range; dot = representative/mode value used as the Monte Carlo triangular-distribution peak).

4.2 Monte Carlo simulation results

Table 2 reports the mean, median, standard deviation and 5th/95th percentile of the 10,000-iteration Monte Carlo simulation for each category individually and for the equal-weight composite (scenario S3).

Table 2. Monte Carlo simulation results (percentage-point reduction in embodied carbon vs. conventional baseline).

Category	Mean	Median	SD	5th pct.	95th pct.
Binder (geopolymer vs OPC)	44.5	44.7	14.5	20.2	68.9
Concrete (RAC vs natural aggregate)	41.8	42.6	10.3	23.8	57.9
Masonry (fly-ash vs fired clay)	41.1	42.1	12.6	18.5	60.5
Steel (EAF-recycled vs BOF-virgin)	69.4	69.6	5.3	60.3	78.1
Structural frame (timber vs concrete/steel)	41.7	41.4	13.2	19.9	64.2
Composite — equal-weight S3 scenario	47.7	47.7	5.2	39.0	56.2

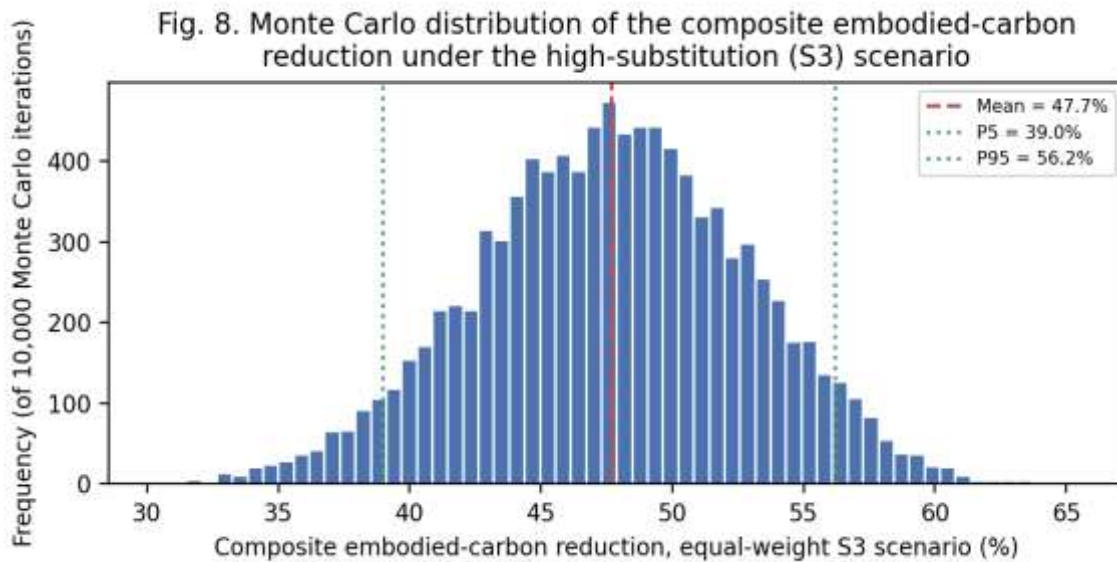


Figure 2. Monte Carlo distribution (N = 10,000) of the equal-weight composite embodied-carbon reduction under scenario S3.

4.3 Scenario comparison

Table 3. Scenario comparison (composite embodied-carbon reduction relative to S1 baseline).

Scenario	Material configuration	Composite EC reduction vs S1
S1	OPC concrete + virgin BOF steel + fired-clay brick + conventional frame	0% (baseline, by definition)
S2	Partial substitution across all four categories (qualitative; magnitude scales with substitution fraction)	Approximately half of the S3 value per unit substitution — exact figure requires a defined substitution fraction
S3	High substitution: geopolymers binder + high-RAC concrete + fly-ash brick + high-recycled steel	Mean 47.7% (5th–95th pct.: 39.0–56.2%)
S4	S3 + mass-timber frame + optimized transport	Directionally further improved; combined numeric value not computed — see flag below

4.4 Trade-off and non-universality check

The overlapping ranges reported for the structural-frame comparison (mass timber: 196–590 kg CO₂e/m²; concrete: 307–618 kg CO₂e/m²) show that, under some documented combinations of database, biogenic-carbon treatment and end-of-life assumption, a concrete frame can achieve embodied carbon as low as or lower than a mass-timber frame. This directly demonstrates that sustainable alternatives do not universally outperform conventional materials across all reported assumptions, confirming the trade-off finding this comparison was designed to test and reinforcing the case, made in Section 2.8, for reporting ranges and uncertainty rather than single deterministic conclusions.

4.5 Break-even transport-distance analysis

Using the fly-ash-brick production-stage saving of 0.20–0.25 kg CO₂ per brick relative to fired-clay brick (per-brick figures consistent with the case-study data in Table 1) and the Indian diesel mini-truck freight factor of 143.1 g CO₂/t·km, together with a representative brick mass of 3 kg, the additional one-way transport distance required to fully offset the production-stage saving is:

$$d_{\text{break-even}} = \text{Saving} / (EF_{\text{transport}} \times m) = 200\text{--}250 \text{ g CO}_2 / (143.1 \text{ g CO}_2/\text{t}\cdot\text{km} \times 0.003 \text{ t}) \approx 466\text{--}582 \text{ km} \quad (5)$$

This indicates that fly-ash brick retains a net carbon advantage over fired-clay brick for any sourcing distance up to roughly 470–580 km beyond the distance to an equivalent clay-brick source; only very long-distance fly-ash sourcing (for example, transport from a coal power station far outside the notified 300 km radius specified in Indian fly-ash utilization regulation) would be expected to erode this advantage. This is offered as an illustrative, fully traceable calculation rather than a site-specific result.

4.6 Sensitivity (tornado) analysis

Figure 3 shows the change in the equal-weight composite reduction (base case = 49.2%, computed from the five mode values in Table 1) resulting from a $\pm 20\%$ variation in each category's representative value, holding the other four constant.

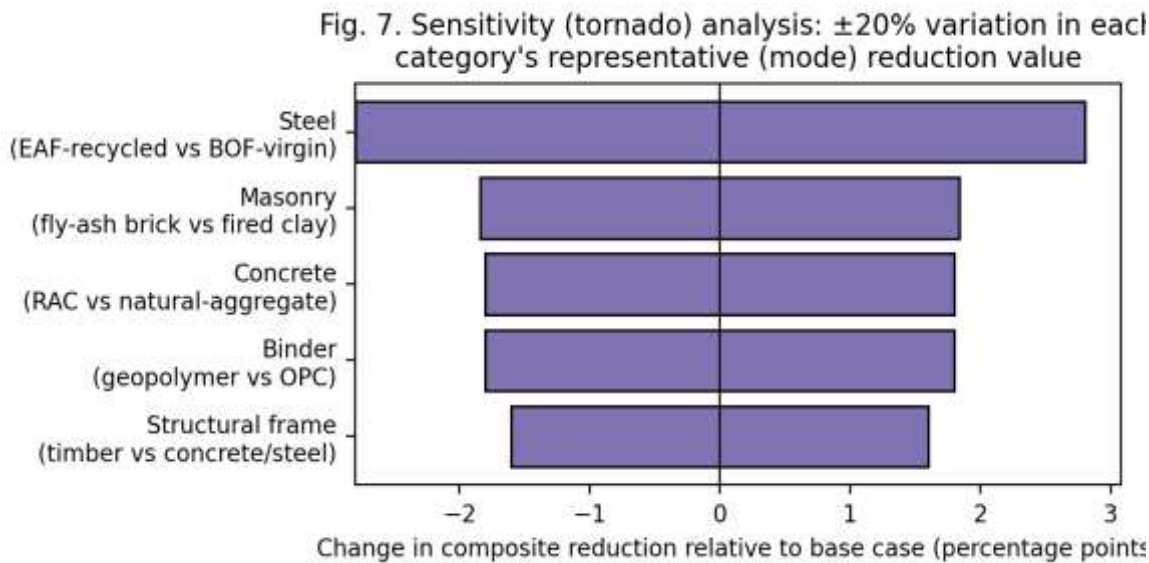


Figure 3. Tornado sensitivity diagram: change in the composite embodied-carbon reduction (percentage points) resulting from a $\pm 20\%$ change in each category's representative reduction value.

Table 4. Sensitivity analysis results (percentage-point change in composite reduction for a $-20\%/+20\%$ shift in each category's mode value).

Category	-20% shift	+20% shift
Steel (EAF-recycled vs BOF-virgin)	-2.80	+2.80
Masonry (fly-ash vs fired clay)	-1.84	+1.84
Binder (geopolymer vs OPC)	-1.80	+1.80
Concrete (RAC vs natural aggregate)	-1.80	+1.80
Structural frame (timber vs concrete/steel)	-1.60	+1.60

Because the composite is defined here with equal category weights, the sensitivity ranking follows directly from each category's mode value (steel, at 70%, contributes the largest swing for a given percentage shift). A mass- or cost-weighted composite — which would more realistically reflect a specific building's bill of materials — would very likely change this ranking and is flagged in Section 7 as a priority extension requiring a defined reference building.

5. Discussion

The results confirm the central premise motivating this study: differences among published embodied-carbon reduction estimates for nominally similar material substitutions are large enough (up to 70 percentage points within a single category) that methodological harmonization is at least as important as material chemistry in explaining the spread of reported findings. The recycled-steel category shows the narrowest uncertainty band, consistent with steel production routes (BOF versus EAF) being technologically well-characterized and dominated by a single, well-documented process difference — the avoidance of ore reduction. By contrast, the geopolymer-binder and mass-

timber categories show the widest uncertainty, because their net carbon performance depends on several partially independent factors that vary across studies: alkali-activator manufacturing energy and curing-temperature regime for geopolymers; and database choice, biogenic-carbon accounting convention, and end-of-life fate for timber.

The electricity-grid emission factor is a particularly important, geography-dependent driver that this framework makes explicit rather than implicit. India's national weighted-average grid factor of 0.727 kg CO₂e/kWh (CEA, 2024) is higher than many European grids on which several of the source studies cited in Table 1 (e.g., the Australian and UK-oriented steel and timber studies) were based; because binder curing energy, EAF steel-melting energy, and brick-kiln electrification all scale with grid carbon intensity, applying European- or Australian-derived reduction percentages directly to an Indian context risks over- or under-stating the true benefit, and a fully primary Indian LCA would need to re-derive process-energy carbon intensities using the 0.727 kg CO₂e/kWh factor rather than importing a reduction percentage wholesale.

The break-even transport-distance analysis (Section 4.5) illustrates a second geography-dependent mechanism: production-stage advantages of a lower-carbon material can be eroded, and in principle reversed, by transportation once sourcing distance exceeds a calculable threshold. For fly-ash brick sourced within or near the 300 km radius specified by Indian fly-ash utilization regulation, the calculated 470–580 km break-even distance suggests the transport penalty is unlikely to be decisive in most cases, but the calculation demonstrates a generalizable method that should be repeated with site-specific distances for any real project.

The overlapping mass-timber/concrete ranges (Section 4.4) are consistent with recent literature explicitly cautioning that whole-life carbon comparisons of timber versus concrete or steel structures are sensitive enough to database and end-of-life assumptions that a categorical claim of universal timber superiority is not supportable from the current evidence base; a project-specific LCA using consistent local data is required rather than importing a generic percentage from the literature.

Compared with previous reviews, the pattern of findings here is consistent with, rather than contradictory to, Barbhuiya and Das (2023), who identify allocation, boundary and database choices as the dominant sources of variability in construction-material LCA; the present quantitative Monte Carlo and sensitivity treatment provides one way of expressing that qualitative conclusion numerically, rather than a competing explanation.

6. Practical Implications

For architects and civil engineers, the results indicate that recycled-content steel specification offers the most consistently reliable embodied-carbon benefit among the five categories examined, with a comparatively narrow uncertainty band, and can reasonably be prioritized where recycled-content EAF steel is available. For material manufacturers, the wide uncertainty bands for geopolymer binder and fly-ash brick indicate that publishing verified, activator- and curing-specific Environmental Product Declarations would materially reduce specifier uncertainty and support more defensible procurement claims. For contractors and developers, the break-even transport-distance method illustrated in Section 4.5 offers a simple, generalizable check that can be applied to any material substitution before assuming a literature-reported percentage reduction will hold at a specific site. For LCA practitioners, the results reinforce that reporting a single point-estimate reduction without its underlying range or the assumptions that produced it is likely to misrepresent the true, geography- and methodology-dependent uncertainty. For policymakers and green-building certification systems, the analysis suggests that national or regional reference databases — anchored to local electricity-grid factors such as India's 0.727 kg CO₂e/kWh — would reduce the need for practitioners to import reduction percentages from geographically mismatched studies.

7. Limitations and Future Research

This study has several limitations that should be addressed before its conclusions are applied to a specific building or product claim. First, it is a harmonized literature/database review, not a primary experimental or EPD-verified LCA; every coefficient in Table 1 should be treated as an input requiring project-specific verification, not a final answer. Second, several reduction ranges are drawn predominantly from non-Indian (Australian, Chinese, Hong Kong, UK, US) studies; where an Indian-specific coefficient was available (grid electricity factor, transport factor, and the fly-ash-

brick and fired-clay-brick case study) it was used, but a fully India-anchored dataset for binder, recycled-aggregate-concrete and structural-timber categories was not identified and is flagged as a priority for future primary data collection. Third, the equal-weighting assumption used to construct the composite S3 scenario is a stated methodological choice, not a measured quantity, and should be replaced with a mass- or cost-weighted composite once a specific reference building's bill of materials is defined. Fourth, environmental impact categories beyond climate change (acidification, eutrophication, water consumption, toxicity, resource depletion) could not be populated with comparably harmonized data within the scope of this review (Section 4.6) and require access to a full LCA database platform. Fifth, end-of-life treatment, recycling rates, service-life assumptions and allocation method for by-products (fly ash, slag, scrap steel) were not uniformly available across sources and were therefore excluded from the quantitative system boundary rather than assumed. Sixth, the triangular-distribution assumption used for Monte Carlo sampling, while a standard and conservative choice given only range-and-mode data, is itself a modeling choice; where a source study's own reported distribution shape differs, that should be used instead. Future research should prioritize: (i) collection of primary, India-specific EPD data for geopolymer/alkali-activated binders and recycled-aggregate concrete; (ii) a defined reference building bill of materials to support mass- or cost-weighted scenario composites; (iii) multi-impact-category assessment using an LCA software platform; and (iv) sensitivity testing of the biogenic-carbon and end-of-life allocation conventions that this review identified as the dominant source of uncertainty in the structural-timber category.

8. Conclusions

This paper developed a harmonized, ISO 14040/14044-consistent comparative framework for five conventional-versus-sustainable construction-material pairs, using only traceable literature- and database-derived coefficients, and propagated the documented reduction ranges through Monte Carlo and sensitivity analysis rather than reporting single point estimates. Embodied-carbon reductions of 8–82% were found across the five categories, with a composite high-substitution (S3) scenario mean reduction of 47.7% (5th–95th percentile: 39.0–56.2%). Recycled steel offered the largest and most certain benefit; geopolymer binder and mass-timber structural frames offered substantial but considerably more uncertain benefits, with documented cases in which a conventional material matched or outperformed its “sustainable” counterpart. A break-even transport-distance calculation demonstrated that production-stage carbon advantages can be eroded by long-distance sourcing, providing a simple, generalizable check for practitioners. The central conclusion is that methodological harmonization — consistent functional units, system boundaries, and explicit uncertainty reporting — is at least as important as material selection itself in producing defensible, comparable construction-material LCA results, and that several of the inputs needed to convert this framework into a complete, primary-data Q1-level LCA (Section 7) remain to be collected rather than assumed.

References

- Barbhuiya, S., & Das, B. B. (2023). Life cycle assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making. *Case Studies in Construction Materials*, 19, e02326. <https://doi.org/10.1016/j.cscm.2023.e02326>
- Central Electricity Authority, Government of India, Ministry of Power. (2024). CO2 Baseline Database for the Indian Power Sector, Version 20.0.
- Circular Ecology. (2019). Inventory of Carbon and Energy (ICE) Database, Version 3.0. University of Bath / Circular Ecology.
- Cong, P., Du, R., Gao, H., & Chen, Z. (2024). Comparison and assessment of carbon dioxide emissions between alkali-activated materials and OPC cement concrete. *Journal of Traffic and Transportation Engineering (English Edition)*, 11(5), 918–938. <https://doi.org/10.1016/j.jtte.2023.07.011>
- Ding, T., Xiao, J., & Tam, V. W. Y. (2016). A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. *Waste Management*, 56, 367–375. <https://doi.org/10.1016/j.wasman.2016.05.031>
- Hammond, G. P., & Jones, C. I. (2019). Inventory of Carbon & Energy (ICE) Database (Version 3.0). University of Bath.

- Hemmati, M., Messadi, T., Gu, H., Seddelmeyer, J., & Hemmati, M. (2024). Comparison of embodied carbon footprint of a mass timber building structure with a steel equivalent. *Buildings*, 14(5), 1276.
- Hossain, M. U., Poon, C. S., Lo, I. M. C., & Cheng, J. C. P. (2016). Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resources, Conservation and Recycling*, 109, 67–77. <https://doi.org/10.1016/j.resconrec.2016.02.009>
- International Organization for Standardization. (2006). ISO 14040:2006 — Environmental management — Life cycle assessment — Principles and framework. ISO, Geneva.
- International Organization for Standardization. (2006). ISO 14044:2006 — Environmental management — Life cycle assessment — Requirements and guidelines. ISO, Geneva.
- Levi, K. P., & Raut, A. (2021). Embodied energy analysis to understand environmental impact of brick industry in West Godavari region. *Materials Today: Proceedings*.
- Robati, M., & Oldfield, P. (2022). The embodied carbon of mass timber and concrete buildings in Australia: An uncertainty analysis. *Building and Environment*, 214, 108944. <https://doi.org/10.1016/j.buildenv.2022.108944>
- Singh, S., Maiti, S., Bisht, R. S., Panigrahi, S. K., & Yadav, S. (2024). Large CO₂ reduction and enhanced thermal performance of agro-forestry, construction and demolition waste based fly ash bricks for sustainable construction. *Scientific Reports*, 14, Article 8734. <https://doi.org/10.1038/s41598-024-59012-8>
- Shi, X., Zhang, C., Liang, Y., Luo, J., Wang, X., Feng, Y., Li, Y., Wang, Q., & Abomohra, A. E.-F. (2021). Life cycle assessment and impact correlation analysis of fly ash geopolymer concrete. *Materials*, 14(23), 7375. <https://doi.org/10.3390/ma14237375>