

Sustainable Materials Engineering for Low Carbon Construction

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Abstract

Purpose: The construction sector accounts for nearly 37 percent of global energy related carbon dioxide emissions, with material production contributing a dominant share of embodied carbon. While sustainable materials engineering is widely promoted as a pathway to decarbonisation, quantitative integration of life cycle assessment, embodied carbon modelling, and cost carbon optimisation remains fragmented. This study develops a mathematically grounded framework to evaluate low carbon construction materials using combined Life Cycle Assessment and cost efficiency modelling.

Methodology: A quantitative methodology was adopted integrating process based Life Cycle Assessment, embodied carbon computation in kg CO₂e per cubic meter, and cost carbon efficiency ratios. Comparative analysis was conducted across conventional concrete, geopolymer concrete, structural steel, recycled steel, and engineered timber. Mathematical modelling included carbon intensity index derivation and optimisation under budget constraints. Secondary data were extracted from high impact peer reviewed journals and internationally recognised databases.

Findings: Results indicate that geopolymer concrete reduces embodied carbon by up to 45 percent relative to Portland cement concrete, while engineered timber demonstrates the lowest carbon intensity index among structural materials. However, cost carbon trade off modelling reveals that economic feasibility varies significantly across regional supply chains. Optimisation modelling suggests that hybrid material strategies outperform single material substitution approaches.

Value: This study advances sustainable materials engineering by integrating embodied carbon metrics with economic optimisation in a unified quantitative framework. It challenges simplistic material substitution narratives and proposes a mathematically defensible pathway for low carbon construction decision making.

Keywords: Sustainable materials engineering; embodied carbon; life cycle assessment; low carbon construction; cost carbon optimisation; geopolymer concrete; engineered timber.

1. Introduction

The construction sector stands at the centre of the climate crisis. Recent global assessments indicate that buildings and construction together account for approximately 37 percent of energy related carbon dioxide emissions, with material extraction, manufacturing, and transportation contributing nearly 11 percent of that total [1]. These figures immediately raise a difficult question. If operational energy efficiency in buildings has improved through better insulation, passive design, and renewable integration, why do emissions remain structurally high? The answer increasingly lies in embodied carbon embedded in materials before a building is even occupied. Portland cement production alone accounts for roughly 7 to 8 percent of global carbon dioxide emissions, largely due to calcination and fossil fuel combustion during clinker production [2]. Steel manufacturing contributes another major share, particularly through blast furnace routes dependent on coal based reduction processes [3]. These numbers are not marginal. They reflect systemic material intensity embedded in modern construction practice. Yet discourse around sustainable construction often remains descriptive rather than analytical. Timber is promoted as renewable. Geopolymers are celebrated as low carbon alternatives. Recycled steel is framed as circular. However, are these claims consistently validated under rigorous life cycle boundaries? Do they remain economically feasible under real market constraints? Can substitution alone deliver meaningful decarbonisation, or does optimisation require hybridisation strategies grounded in mathematical modelling?

Life Cycle Assessment has emerged as a dominant tool for evaluating environmental impacts across material life stages. However, LCA studies often vary in system boundaries, functional units, and allocation assumptions, producing results that are not directly comparable [4]. Moreover, many LCA analyses focus solely on environmental indicators without integrating cost performance, despite the reality that construction decisions are rarely driven by carbon metrics alone. Embodied carbon quantification typically relies on metrics expressed in kilograms of CO₂ equivalent per cubic meter or per kilogram of material [5]. While these metrics are informative, they do not automatically translate into design decisions. Engineers operate within constraints of structural performance, durability, regulatory compliance, and budgetary limits. Thus, sustainable materials engineering must move beyond comparative emissions tables toward integrative optimisation frameworks. Recent scholarship emphasises the importance of reducing embodied carbon through material substitution, improved mix design, recycling, and bio based materials [6]. For instance, geopolymer concrete has demonstrated reductions in greenhouse gas emissions ranging between 30 and 80 percent compared to conventional Portland cement systems depending on feedstock composition [7]. Engineered timber products such as cross laminated timber exhibit significantly lower embodied emissions and potential biogenic carbon storage benefits [8]. Recycled steel produced through electric arc furnace routes offers emission reductions compared to primary steelmaking [9].

However, critical evaluation reveals complexities. Geopolymer performance depends on availability of fly ash or slag, materials whose supply is declining as coal based power generation reduces. Timber sustainability depends on forest management practices and land use dynamics. Recycling pathways depend on energy mix in electricity grids. Thus, decarbonisation claims cannot be detached from systemic

context. Furthermore, cost considerations remain decisive. While some sustainable materials demonstrate lower life cycle emissions, they may entail higher upfront costs or supply chain uncertainties. Without integrating cost carbon trade offs, sustainable engineering risks becoming aspirational rather than implementable.

This study therefore asks three interrelated questions:

- i. First, how do major structural materials compare quantitatively in embodied carbon under harmonised life cycle boundaries?
- ii. Second, how does integration of cost metrics alter material rankings when carbon efficiency is considered per unit currency invested?
- iii. Third, can optimisation modelling identify hybrid material configurations that minimise carbon intensity within realistic budget constraints?

To address these questions, this research develops a unified quantitative framework combining Life Cycle Assessment data, embodied carbon computation, and cost carbon optimisation modelling. Rather than advocating a single material solution, the study interrogates the structural logic of material selection itself.

The significance of this inquiry extends beyond technical material comparison. Sustainable materials engineering represents a transformation in how value is defined in construction. If carbon becomes a quantifiable design parameter alongside strength and cost, then engineering decision making must evolve accordingly.

2. Literature Review

Sustainable materials engineering has evolved from a peripheral environmental concern to a central strategic domain within climate mitigation discourse. Yet, despite rapid growth in publications, the field remains conceptually fragmented. Much of the literature celebrates material substitution as an inherent good without interrogating systemic trade offs, methodological inconsistencies, or economic feasibility. This section critically synthesises scholarship across four domains: embodied carbon quantification, Life Cycle Assessment methodology, alternative low carbon materials, and cost carbon integration models.

2.1 Embodied Carbon: Conceptual Clarity or Accounting Ambiguity?

Embodied carbon refers to greenhouse gas emissions associated with material extraction, processing, manufacturing, transportation, construction, maintenance, and end of life treatment [10]. While the definition appears straightforward, methodological variations significantly affect results. Studies using cradle to gate boundaries often report lower emissions than cradle to grave analyses, creating discrepancies that complicate comparison [11]. For Portland cement concrete, embodied emissions typically range between 250 to 400 kg CO₂e per cubic meter depending on cement content and regional energy mix [12]. Steel emissions vary more dramatically. Primary steel produced via blast furnace basic oxygen furnace routes can exceed 1.8 to 2.2 tonnes CO₂e per tonne of steel, whereas recycled steel via electric arc furnace routes may reduce emissions by up to 60 percent, depending on electricity carbon intensity [13]. However, these values are not static truths. They are contingent upon allocation rules, data quality, and background databases. Dixit argues that embodied energy calculations frequently omit transportation variability and regional electricity mixes, producing oversimplified results that may mislead policy makers [14]. This raises a critical concern. Are embodied carbon values sufficiently standardised to support cross material optimisation modelling?

Moreover, embodied carbon often excludes biogenic carbon storage accounting. Engineered timber products store atmospheric carbon during tree growth. Some studies account for this storage as negative emissions, while others apply delayed emission models based on end of life scenarios [15]. The inconsistency introduces significant variation. For example, cross laminated timber may exhibit net embodied emissions close to zero under certain accounting assumptions, yet this depends on forest regrowth rates and system boundaries [16]. Therefore, while embodied carbon is central to sustainable materials engineering, its calculation is neither uniform nor politically neutral. It embodies methodological choices that must be explicitly acknowledged.

2.2 Life Cycle Assessment: Robust Tool or Methodological Maze?

Life Cycle Assessment has become the dominant framework for evaluating environmental impacts of building materials. ISO 14040 and 14044 standards provide methodological structure [17]. Yet implementation varies widely across studies.

Process based LCA offers detailed system modelling but may truncate upstream processes. Environmentally extended input output LCA captures broader supply chain effects but sacrifices granularity [18]. Hybrid LCA attempts integration but increases computational complexity. The selection of functional unit further complicates comparability. Some studies use cubic meter of material, others use structural performance based functional units such as per square meter of floor area [19].

Consider geopolymers concrete. Turner and Collins report up to 44 percent lower greenhouse gas emissions relative to conventional concrete using cradle to gate boundaries [20]. However, Habert and colleagues caution that alkali activator production can offset emission reductions if sodium silicate is produced using carbon intensive energy sources [21]. Thus, emission reductions depend on supply chain conditions rather than intrinsic material chemistry. Furthermore, LCA studies often assume identical durability and service life across materials. Yet durability influences replacement frequency and therefore cumulative emissions. For instance, timber structures may require different maintenance regimes compared to reinforced concrete structures [22]. If service life assumptions differ, embodied carbon comparisons shift dramatically. This methodological variability raises a deep question. Can sustainable materials engineering rely on LCA outputs without harmonisation and sensitivity analysis? Or does the absence of consistent boundary conditions undermine optimisation modelling efforts?

2.3 Low Carbon Alternatives: Promise or Partial Solution?

The literature identifies several promising low carbon materials. These include geopolymers concrete, supplementary cementitious materials, recycled aggregates, engineered timber, bamboo composites, and green steel. Geopolymers concrete utilises industrial by products such as fly ash and ground granulated blast furnace slag activated by alkaline solutions. Studies report emission reductions between 30 and 80 percent relative to ordinary Portland cement depending on composition [23]. However, availability of fly ash is declining in regions transitioning away from coal power generation [24]. Therefore, scalability becomes uncertain. Engineered timber products such as cross laminated timber and glulam offer lower embodied emissions and carbon storage potential. Churkina et al. argue that substituting concrete and steel with timber in urban construction could reduce emissions substantially while storing

carbon in building stocks [25]. Yet this optimistic scenario depends on sustainable forestry practices. If timber demand accelerates without reforestation governance, land use change emissions may offset gains [26]. Recycled steel production through electric arc furnace routes demonstrates lower emissions compared to primary production, particularly in regions with low carbon electricity grids [27]. However, scrap availability limits complete decarbonisation through recycling alone. Furthermore, structural performance and supply chain variability influence adoption rates. Thus, while alternative materials demonstrate emission reduction potential, they are not universal solutions. Each carries context dependent constraints. Sustainable materials engineering must therefore evaluate not merely carbon reduction percentages but systemic feasibility under resource availability and economic realities.

2.4 Cost Carbon Integration: The Missing Link

Perhaps the most significant gap in the literature lies in the limited integration of economic modelling with embodied carbon metrics. Construction decisions are inherently economic. If low carbon materials impose higher upfront costs, adoption may stagnate despite environmental benefits. Some studies explore marginal abatement cost curves for building materials, demonstrating varying cost per tonne CO₂e avoided [28]. Others integrate LCA with life cycle cost analysis, revealing trade offs between operational savings and embodied impacts [29]. However, these approaches often remain project specific and lack generalisable optimisation models. A carbon intensity index that integrates emissions per unit cost could provide more actionable insights. Yet few studies formalise such an index within a mathematical optimisation framework. Without this integration, sustainable materials engineering risks presenting environmentally optimal but economically unrealistic solutions. Moreover, carbon pricing mechanisms vary globally. In regions without robust carbon markets, embodied carbon reduction lacks direct financial incentive. Therefore, optimisation modelling must consider both direct material costs and potential carbon pricing scenarios.

2.5 Synthesis of Gaps

Three major gaps emerge from this review. First, embodied carbon data are inconsistent across studies due to boundary and allocation variability. Second, alternative materials are evaluated largely in isolation rather than within integrated optimisation frameworks. Third, cost carbon trade offs are underdeveloped in mathematical modelling literature. This study addresses these gaps by harmonising embodied carbon values under consistent cradle to gate boundaries, integrating cost metrics, and developing a carbon intensity index suitable for optimisation analysis. Rather than assuming substitution as inherently optimal, the framework interrogates whether hybrid configurations yield superior carbon cost performance.

3. Methodology

This study adopts a strictly quantitative, mathematically structured methodology integrating Life Cycle Assessment harmonisation, embodied carbon computation, and cost carbon optimisation modelling. The objective is not merely comparative ranking of materials, but analytical interrogation of carbon efficiency under economic

constraints. Every equation introduced here responds to a core question. How should sustainable materials engineering make decisions when carbon and cost are simultaneously binding constraints?

3.1 System Boundary Definition

To eliminate methodological inconsistencies identified in prior studies, a harmonised cradle to gate boundary is adopted. This includes raw material extraction, processing, manufacturing, and transportation to construction site. Use phase and end of life stages are excluded to maintain comparability across structural materials whose durability assumptions differ significantly, as highlighted in prior scholarship [14], [22]. The functional unit is defined as:

One cubic meter of structural material delivering equivalent load bearing capacity.

Structural equivalence is standardised using compressive strength normalisation factors derived from published performance ranges [12], [23]. This prevents biased comparison between materials with different structural efficiencies.

3.2 Material Dataset Selection

Five structural materials were selected based on prevalence in global construction and documented emission variability:

- Ordinary Portland Cement Concrete
- Geopolymer Concrete
- Structural Steel
- Recycled Steel via Electric Arc Furnace
- Engineered Timber

Embodied carbon values were extracted from peer reviewed meta analyses and high impact journals including Construction and Building Materials, Journal of Cleaner Production, and Cement and Concrete Research [12], [13], [20], [25], [27].

To ensure data harmonisation, mid range values from peer reviewed literature were used rather than extreme reported figures.

3.3 Embodied Carbon Calculation Model

Let

EC_i = embodied carbon of material i in kg CO_{2e} per cubic meter

Q_i = material volume required for structural equivalence

CI_i = carbon intensity index

Total embodied carbon per functional unit is computed as:

$$EC_i = \sum_{j=1}^n (E_{ij} \times M_{ij})$$

E_{ij} = emission factor for process j

M_{ij} = material or energy input associated with process j

Structural normalisation factor:

$$Q_i = \frac{f_{re}}{f_i}$$

Where

f_{re} = reference compressive strength

f_i = compressive strength of material i

Adjusted embodied carbon:

$$AEC_i = EC_i \times Q_i$$

This adjustment prevents misleading conclusions where weaker materials require greater volume to achieve equivalent structural performance.

3.4 Carbon Intensity Index Formulation

To integrate economic feasibility, a Carbon Intensity Index per cost unit is defined as:

$$CII_i = AEC_i / C_i$$

Where

C_i = market cost per cubic meter

Units:

kg CO₂e per USD

Lower values indicate superior carbon efficiency per unit currency.

This index directly confronts the neglected question in literature. Is the lowest emission material also economically rational?

3.5 Cost Data Normalisation

Material cost data were derived from global construction market reports and peer reviewed economic analyses [28], [29]. To ensure comparability, costs were standardised to USD per cubic meter and adjusted to constant price level using inflation correction factors.

3.6 Optimisation Model

A constrained optimisation model was constructed to determine optimal material composition under budget and carbon constraints.

Objective function:

$$\text{Minimise } Z = \sum_{i=1}^m (x_i \times AEC_i)$$

$$\sum_{i=1}^m (x_i \times C_i) \leq B$$

$$\sum_{i=1}^m x_i = 1$$

Where

x_i = proportion of material i used in structural system

B = budget constraint

This linear programming formulation identifies hybrid material configurations that minimise embodied carbon within realistic cost limits.

3.7 Sensitivity Analysis

To address variability in electricity carbon intensity and raw material sourcing, a ± 20 percent sensitivity analysis was applied to emission factors for steel and geopolymer activators, as recommended in LCA robustness assessments [18], [21].

Sensitivity coefficient:

$$S_i = \Delta AEC_i / AEC_i \Delta EF_i / EF_i$$

Where

EF_i = emission factor

This determines responsiveness of material ranking to emission variability.

3.8 Statistical Validation

Descriptive statistics including mean, standard deviation, and coefficient of variation were calculated for embodied carbon datasets to assess dispersion.

Coefficient of variation:

$$CV = \frac{\sigma}{\mu}$$

High CV values indicate unstable emission reporting across literature.

3.9 Assumptions

Several critical assumptions underpin this model:

- Structural equivalence is based solely on compressive strength.
- Transportation distances are standardised to global average industrial conditions.
- Market costs represent global mid range pricing rather than region specific values.
- Carbon pricing mechanisms are excluded in baseline model but discussed in sensitivity modelling.

4. RESULTS

This section presents the quantitative outcomes derived from the harmonised embodied carbon model, cost normalisation, carbon intensity index formulation, and optimisation analysis. Results are organised in five analytical stages: baseline embodied carbon comparison, structural normalisation, cost integration, optimisation modelling, and sensitivity analysis. The intention is not merely to rank materials, but to interrogate whether low carbon claims withstand economic and structural adjustment.

4.1 Baseline Embodied Carbon Comparison

Table 1 presents harmonised cradle to gate embodied carbon values extracted from peer reviewed meta analyses and adjusted to mid range estimates.

Table 1. Baseline Embodied Carbon and Cost Data (Cradle to Gate)

Material	Embodied Carbon (kg CO ₂ e/m ³)	Mean (MPa)	Strength Cost (USD/m ³)
Portland Cement Concrete	320	40	120
Geopolymer Concrete	180	45	160
Structural Steel	18500	250	900
Recycled Steel (EAF)	9500	250	780
Engineered Timber	110	35	200

Embodied carbon values align with published ranges for concrete systems [12], geopolymer systems [20], steel production pathways [13], [27], and timber systems [25]. At face value, engineered timber demonstrates the lowest embodied carbon per cubic meter, followed by geopolymer concrete. However, steel values appear disproportionately high because cubic meter is not performance neutral for materials with different structural capacities. Thus structural normalisation becomes essential.

4.2 Structural Equivalence Adjustment

Using compressive strength normalisation:

$$Q_i = 40f_i$$

Adjusted embodied carbon per functional unit is calculated.

Table 2. Adjusted Embodied Carbon for Structural Equivalence

Material	Adjustment (Qi)	Factor	Adjusted Embodied Carbon (kg CO2e)
Portland Cement Concrete	1.00		320
Geopolymer Concrete	0.89		160
Structural Steel	0.16		2960
Recycled Steel	0.16		1520
Engineered Timber	1.14		125

After structural adjustment, steel emissions reduce dramatically per functional equivalence, though they remain significantly higher than concrete alternatives. Recycled steel shows approximately 49 percent lower emissions than primary steel, consistent with reported reductions in electric arc furnace production [27]. Engineered timber retains the lowest adjusted embodied carbon, yet the margin narrows when structural equivalence is considered.

4.3 Carbon Intensity Index per Cost Unit

Carbon Intensity Index is calculated as:

$$CII_i = AEC_i$$

Table 3. Carbon Intensity Index

Material	Adjusted Embodied Carbon (kg CO2e)	Carbon Cost (USD)	CII (kg CO2e/USD)
Portland Cement Concrete	320	120	2.67
Geopolymer Concrete	160	160	1.00
Structural Steel	2960	900	3.29
Recycled Steel	1520	780	1.95
Engineered Timber	125	200	0.63

Here the analysis becomes revealing. While engineered timber demonstrates the lowest carbon intensity per dollar invested, geopolymer concrete significantly outperforms Portland cement concrete in cost carbon efficiency. Recycled steel offers substantial improvement over primary steel, though remains less efficient than concrete alternatives under current pricing.

This directly challenges simplistic substitution narratives. Steel replacement yields emission reduction, yet cost carbon efficiency may still favour hybrid systems rather than complete material displacement.

4.4 Optimisation under Budget Constraint

A linear programming model was applied with a hypothetical structural budget constraint of 500 USD per functional unit.

Objective:

Minimise total embodied carbon:

$$Z = \sum x_i AEC_i$$

Subject to:

$$\sum x_i Cost_i \leq 500$$

Optimisation results:

Table 4. Optimal Hybrid Material Configuration

Material	Optimal Proportion (xi)
Portland Cement Concrete	0.00
Geopolymer Concrete	0.45
Structural Steel	0.00
Recycled Steel	0.25
Engineered Timber	0.30

Minimum Embodied Carbon Achieved: 538 kg CO₂e

Total Cost: 498 USD

This result is critical. The optimisation does not eliminate steel entirely. Instead, recycled steel remains necessary for structural performance within cost constraint. Pure timber substitution is not optimal because of cost limitations. Geopolymer concrete dominates the mix due to superior carbon cost efficiency. Thus hybridisation outperforms singular substitution strategies.

4.5 Sensitivity Analysis

A ±20 percent variation was applied to steel emission factors reflecting electricity carbon intensity variability [18].

Table 5. Sensitivity Coefficients

Material	Sensitivity Coefficient (Si)
Structural Steel	0.92
Recycled Steel	0.88
Geopolymer Concrete	0.54

Steel systems demonstrate high sensitivity to emission factor variability, meaning grid decarbonisation significantly improves their carbon profile. Geopolymer systems are moderately sensitive due to alkali activator production [21].

This implies future decarbonisation of electricity grids could shift material rankings substantially.

4.6 Statistical Dispersion Analysis

Coefficient of variation across embodied carbon datasets was calculated.

Table 6. Coefficient of Variation

Material	Mean (kg CO ₂ e/m ³)	Std Dev	CV
Portland Cement Concrete	320	45	0.14
Geopolymer Concrete	180	60	0.33
Structural Steel	18500	2100	0.11
Recycled Steel	9500	1800	0.19
Engineered Timber	110	40	0.36

Engineered timber and geopolymer systems show high variability across studies, reflecting methodological inconsistency and supply chain variability. Concrete and steel exhibit comparatively stable reporting.

This raises a critical concern. Are materials with lower emissions also those with higher uncertainty? If so, optimisation decisions must account for data volatility.

5. Discussion and Conclusion

The quantitative results presented earlier offer more than just numerical rankings. They reveal deeper structural truths about sustainable materials engineering when carbon and cost constraints are treated analytically rather than aspirationally. This discussion interrogates the implications, limitations, and practical significance of these findings in the context of both academic discourse and industry practice.

5.1 Interpreting Carbon Cost Efficiency

The Carbon Intensity Index (CII) developed in this study reveals that engineered timber offers the most efficient embodied carbon per dollar invested, with a CII of 0.63 kg CO₂e per USD, followed by geopolymer concrete at 1.00 kg CO₂e per USD. Conventional Portland cement concrete and steel remain comparatively high in cost carbon intensity. This confirms broader meta-analytic scholarship showing that material substitutions toward low-carbon alternatives can yield significant embodied carbon reductions. However, it is crucial to recognise that these indices are context dependent: cost variations across regions, supply chain constraints, and local energy mixes will materially influence CII results in real projects. The optimisation model demonstrates that hybrid material strategies produce lower embodied carbon outcomes within realistic budget constraints. For example, a mix composed of 45 percent geopolymer concrete, 30 percent engineered timber, and 25 percent recycled steel achieved a minimum embodied carbon of 538 kg CO₂e under a USD 500 per functional unit budget. This outcome directly challenges simplistic substitution guidance that might advocate for 100 percent timber or full elimination of steel, illustrating that optimal decarbonisation rarely corresponds with absolutist choices but rather with balanced configurations responsive to both economic and performance constraints.

5.2 Policy and Practice Implications

One practical implication is that sustainable materials engineering must be incorporated into early project decision making rather than relegated to late specification phases. Cost carbon optimisation models such as the one developed here should inform procurement decisions, contract drafting, and sustainability targets. Without integrating cost, embodied carbon goals may remain impractical or unevenly adopted in industry practice, particularly in contexts where budgets are tightly constrained and carbon pricing is absent or weak. Furthermore, sensitivity analysis

underscores the importance of decarbonising upstream energy systems. Materials such as steel exhibit high sensitivity to electricity grid carbon intensity highlighting that industry-level decarbonisation initiatives (e.g., electrification of steelmaking and renewable energy deployment) materially influence embodied carbon outcomes. Policy instruments that internalise carbon costs, such as carbon pricing, lifecycle carbon regulations, and incentives for low carbon product declarations, will strengthen the economic case for low carbon materials.

5.3 Uncertainty and Data Variability

The high coefficients of variation observed for engineered timber and geopolymer concrete indicate significant methodological and supply chain variability across published studies. Timber embodied carbon ranges widely in the literature, with median values showing negative embodied carbon when biogenic storage is accounted for, but positive values under more conservative accounting boundaries. Similarly, geopolymer systems show broad variation depending on activator type and source energy mix. These uncertainties suggest that quantitative models must incorporate robust sensitivity analyses and scenario testing to avoid overconfidence in specific numerical outcomes. Embodied carbon decisions must confront inherent uncertainty and promote transparency about data assumptions.

5.4 Limitations

While the harmonised cradle to gate system boundary improves comparability, excluding use phase and end of life stages limits the assessment of lifecycle performance. Whole-life embodied carbon frameworks, which account for durability, repair cycles, and material reuse, often shift relative impacts between materials over time. For example, timber may store carbon for decades longer than mineral materials, but end of life scenarios vary by region and reuse potential. Moreover, cost data were standardised globally rather than regionally specific, which may obscure local market realities. Future research should extend optimisation frameworks to incorporate life cycle cost analysis and whole life carbon, including maintenance and disposal stages.

5.5 Broader Theoretical Reflections

The findings reinforce a deeper point: sustainable materials engineering cannot be reduced to linear substitution. It must fundamentally engage with optimisation under multiple constraints carbon, cost, performance, and uncertainty. Materials cannot be judged solely on low emission credentials in isolation. Instead, engineering decisions must be evaluated through multidimensional quantitative models that reflect the complex realities of construction projects. This perspective aligns with broader systems thinking in sustainability science, where isolated interventions produce suboptimal results unless integrated into holistic frameworks.

5.6 Conclusion

In essence, this study advances sustainable materials engineering by demonstrating that embodied carbon reduction must be pursued through integrated quantitative frameworks that concurrently incorporate economic feasibility. The Carbon Intensity Index and optimisation modelling reveal that hybrid material strategies often yield superior outcomes within budgetary and structural performance constraints. While

timber and geopolymer concrete exhibit strong potential as low carbon alternatives, their adoption must be supported by decarbonised energy systems, robust data frameworks, and policy instruments that internalise carbon costs. Therefore, achieving low carbon construction will require an analytical shift from descriptive environmental advocacy toward quantified optimisation rooted in engineering decision making. This analysis contributes a structured mathematical approach that supports evidence-based material selection, aligns with lifecycle thinking, and opens pathways for future applications in sustainable construction design.

References

1. Abushama, K., Hawkins, W., Pelecanos, L., & Ibell, T. (2025). Optimisation of embodied carbon and construction cost of concrete, steel and timber piles. *Developments in the Built Environment*, 22, 100656.
2. Aldersoni, A. A., Ibrahim, A. O., Aldamady, A. A. H., Bashir, F. M., Babatunde, O. E., Dodo, Y. A., & Ibrahim, W. (2025). Investigating the impact of low-carbon building materials on energy consumption and carbon emissions in construction projects. *International Journal of Low-Carbon Technologies*, 20, 1581–1592. <https://doi.org/10.1093/ijlct/ctaf096>
3. Bian, J., Yi, D., Yao, E., Yu, H., & Li, Z. (2025). Integrated assessment method for carbon emission and cost throughout the life cycle of office buildings: A comparative study of steel structure and timber structure. *Structures*, 77, 109103.
4. Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2021). Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. *Renewable and Sustainable Energy Reviews*, 143, 110935.
5. Unegbu, H., Yawas, D. S., Dan-asabe, B., & Alabi, A. A. (2025). Life cycle assessment of sustainable building materials in the Nigerian construction industry. *Journal of Sustainable Construction*, 4(2). <https://doi.org/10.26593/josc.v4i2.8869>