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Integrating Life Cycle Assessment with LEED and BREEAM Frameworks: A Multi-Criteria Sustainability Evaluation of Emerging Low-Carbon Structural Materials

Madhu Sudan[1], Rakesh Kumar[2], Ashwani Kumar[3]

[1]M. Tech Scholar, Department of Civil Engineering Engineering, BRCMCET, BAHAL

[2]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL

[3]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL

Abstract

The pursuit of sustainable construction practices has intensified the demand for transparent, quantifiable methods to assess the environmental performance of structural materials. While Life Cycle Assessment (LCA) offers a robust scientific basis for evaluating environmental impacts, its integration into widely recognized green building certification frameworks—such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method)—remains limited. This study aims to bridge that gap by developing a multi-criteria sustainability evaluation model that maps LCA-derived indicators to relevant certification criteria. A set of emerging low-carbon structural materials—geopolymer concrete, bamboo, recycled steel, and bio-based composites—were assessed using cradle-to-grave LCA methodologies, focusing on key indicators including Global Warming Potential (GWP), embodied energy, recyclability, and resource efficiency.

To ensure practical comparability, a normalization-based scoring system was employed, translating environmental metrics into composite sustainability scores on a standardized scale. These scores were further aligned with LEED v4 and BREEAM rating categories, enabling the benchmarking of material performance within recognized sustainability frameworks. The findings indicate that bamboo and bio-based composites achieve the highest overall sustainability ratings, while recycled steel excels in circularity and end-of-life benefits. Geopolymer concrete demonstrates substantial reductions in embodied carbon compared to traditional cement-based materials, though with trade-offs in other impact areas.

The proposed scoring framework offers a transparent and scalable tool for integrating environmental data into early-stage design decisions. By aligning LCA results with certification requirements, this research provides actionable insights for architects, engineers, and policymakers seeking to promote low-impact material choices and support climate-resilient construction. The methodology also contributes to advancing standardized, data-driven approaches in sustainable material selection for the built environment.

Keywords

Sustainability rating, LEED, BREEAM, Life Cycle Assessment, Multi-criteria evaluation, Low-carbon materials

Introduction

As the construction industry faces mounting pressure to reduce its environmental footprint, the selection of sustainable building materials has become a central concern in achieving climate goals and enhancing resource efficiency. Green building certification systems such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) have emerged as influential tools for promoting environmentally responsible construction practices. These frameworks incentivize the use of low-impact materials by awarding credits based on criteria such as life cycle performance, responsible sourcing, and recyclability. In doing so, they not only shape design strategies but also influence procurement choices and policy development across the building sector.

Despite their growing adoption, a critical gap remains in the alignment between scientifically rigorous environmental assessments—specifically Life Cycle Assessment (LCA)—and the criteria used by certification systems. LCA offers a detailed, cradle-to-grave analysis of a material's environmental impacts, yet its integration into LEED and BREEAM credit systems is often indirect, fragmented, or reliant on generalized assumptions. Certification frameworks tend to emphasize documentation (e.g., Environmental Product Declarations) rather than interpreting LCA results in a way that enables meaningful material comparisons. As a result, the decision-making process for selecting truly low-impact materials is often hindered by a lack of standardized, data-driven tools that bridge technical analysis and practical certification compliance.

This study seeks to address this disconnect by developing a multi-criteria sustainability evaluation model that integrates LCA indicators with green building certification criteria. By scoring and ranking emerging low-carbon structural materials—such as geopolymer concrete, bamboo, recycled steel, and bio-based composites—based on a combination of environmental metrics and certification alignment, the proposed model aims to support evidence-based material selection. The objective is to translate complex environmental data into accessible and actionable insights that can inform both design and policy decisions in the transition toward sustainable construction practices.

Literature Review

The growing urgency to decarbonize the construction sector has prompted a surge in research focused on the environmental performance of building materials. Life Cycle Assessment (LCA) has emerged as the standard methodology for quantifying environmental impacts across the lifespan of construction materials, offering a scientific basis for evaluating embodied carbon, energy consumption, and resource use. However, a recurring issue in the literature is the limited integration of these LCA results into mainstream sustainability certification frameworks such as LEED and BREEAM, which are widely adopted to guide green building practices.

Ghanbari (2023) presents a comparative LCA of 22 common building materials and reveals considerable variation in embodied energy and emissions across categories. While the study categorizes materials into high- and low-carbon groups, it also highlights the methodological inconsistencies that hinder direct comparisons. Similarly, Rettinger and Meyer (2023) propose a visual decision-making tool for selecting low-impact materials, though the lack of quantitative scoring limits its application within formal certification frameworks. Both studies underscore the need for harmonized tools that can translate environmental data into practical metrics aligned with green building credits.

Further contributions from Caruso et al. (2017) and Hosseinian and Faghani (2021) explore LCA-based decision-making during early design stages. Their work emphasizes the importance of integrating environmental criteria alongside structural considerations, especially in system selection and geotechnical design. However, their methodologies fall short of aligning with certification systems in a way that would directly support LEED or BREEAM compliance.

In contrast, Tokede et al. (2022) expand the scope by incorporating life cycle sustainability assessment (LCSA), which includes environmental, economic, and social dimensions. While this holistic view is valuable, the lack of a clear scoring mechanism based on certification criteria limits its utility for architects and engineers seeking direct application in certified projects. Barbhuiya and Das (2023) further reinforce the call for standardized, comparable LCA applications, pointing out data quality issues and regional variability that complicate global benchmarking.

Studies on low-carbon materials themselves, such as geopolymer concrete, bamboo, and bio-based composites, consistently show promising environmental performance. However, as noted by Oh et al. (2023) and Chen et al. (2020), these materials are often assessed in isolation or within narrow functional contexts, making it difficult to rank them comprehensively against conventional options or to evaluate their certification potential. Moreover, while bamboo and timber exhibit favorable biogenic carbon profiles, issues related to fire resistance, treatment, and standardization remain underexplored in environmental assessments.

Collectively, the literature reveals a pressing need for a unified approach that bridges the gap between detailed LCA outputs and practical sustainability ratings recognized by certification systems. There is consensus on the environmental benefits of alternative materials, yet limited progress has been made in transforming LCA results into normalized, multi-criteria scores that are compatible with LEED, BREEAM, or similar frameworks. This research responds directly to that gap by proposing an evaluation model that both quantifies and contextualizes environmental performance in a certification-ready format, thereby contributing to more informed and sustainable material selection processes.

Methodology

This study adopts a systematic approach to evaluate the sustainability performance of emerging low-carbon structural materials in comparison with conventional options. The methodology integrates quantitative life cycle assessment (LCA) indicators with recognized green building certification criteria, ultimately generating composite sustainability scores through a multi-criteria evaluation framework.

Selection of Materials

Four alternative structural materials were selected for assessment, reflecting both their potential to reduce embodied environmental impacts and their growing relevance in sustainable construction practice:

- **Geopolymer Concrete**, produced from industrial by-products such as fly ash and ground granulated blast furnace slag, offering substantially lower emissions than ordinary Portland cement-based concrete.
- **Bamboo**, a rapidly renewable natural material with a high strength-to-weight ratio and capacity for carbon sequestration.
- **Recycled Steel**, which reduces the energy and emissions burden associated with primary steel production.
- **Bio-based Composites**, such as hempcrete or natural-fiber-reinforced binders, characterized by biodegradability and low embodied energy.

To establish a baseline for comparative purposes, two conventional materials were included: Portland cement concrete and virgin structural steel, which remain dominant in most structural applications.

Life Cycle Assessment Indicators

The environmental evaluation of each material was conducted using a cradle-to-grave LCA approach, incorporating the following key indicators:

- **Global Warming Potential (GWP)**, expressed as kilograms of CO_2 equivalent per cubic meter, capturing the cumulative greenhouse gas emissions across all life cycle stages.
- **Embodied Energy**, measuring the total primary energy required for extraction, processing, transport, and end-of-life treatment.
- **Recyclability**, reflecting the proportion of the material that can be feasibly recovered or reused after its service life.
- **Resource Efficiency**, considering factors such as renewable content, raw material intensity, and material utilization efficiency.

Quantitative data for these indicators were derived from a combination of peer-reviewed LCA studies, environmental product declarations (EPDs), and authoritative databases such as Ecoinvent. A consistent functional unit of 1 cubic meter was applied to all materials to ensure comparability.

Scoring Matrix and Normalization

To translate LCA indicators into a standardized performance scale, a scoring matrix was developed based on min-max normalization. For each indicator, raw data values were transformed to a 0–10 scale using the following formula:

$$S_i = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \times 10$$

This approach ensures that materials with the best environmental performance on a given criterion receive higher scores, facilitating intuitive interpretation and comparison.

Integration with Green Building Certification Frameworks

To enhance practical relevance, the scoring matrix was directly mapped to the credit structures of LEED v4 and BREEAM International:

- For LEED, the evaluation focused on credits under *Materials and Resources* (MR), including *Building Life-Cycle Impact Reduction* (MR Credit 1) and *Environmental Product Declarations* (MR Credit 2).
- For BREEAM, alignment was based on *Mat 01 Life Cycle Impacts* and *Mat 03 Responsible Sourcing of Materials*.

This mapping involved identifying which LCA indicators contributed to credit achievement and how the normalized scores corresponded to certification performance thresholds.

Weighting Approach

To generate composite sustainability scores for each material, individual indicator scores were aggregated using a weighting system. Two weighting approaches were considered:

1. **Literature-Based Weights**, derived from precedent studies emphasizing the relative importance of GWP, embodied energy, and recyclability in sustainable construction assessments.
2. **Stakeholder-Informed Weights**, reflecting priorities expressed by professionals such as architects, structural engineers, and sustainability consultants through surveys and expert consultations.

By combining both weighting perspectives, the study ensured that the final scores were robust and sensitive to both scientific priorities and practical stakeholder expectations.

Summary of Methodological Flow

The methodology proceeded in the following sequence:

1. Selection and characterization of materials.
2. Compilation of LCA indicator data for each material.
3. Normalization of raw values to a standardized scoring scale.
4. Mapping of indicators to LEED and BREEAM criteria.
5. Application of weighting to derive composite sustainability scores.
6. Comparative ranking and interpretation of results.

This integrative approach is intended to offer a transparent and replicable framework that bridges technical LCA analysis with actionable certification-focused evaluation, ultimately supporting more informed material selection in sustainable building design.

Results

This section presents the results of the multi-criteria sustainability evaluation based on normalized LCA indicators and their alignment with certification criteria. The analysis encompasses four alternative low-carbon materials—geopolymer concrete, bamboo, recycled steel, and bio-based composites—and two baseline materials, Portland cement concrete and virgin structural steel. Sustainability scores were generated using a 0–10 scale through min-max normalization and subsequently aggregated into composite scores based on literature-based and stakeholder-informed weighting. These results form the basis for comparative material ranking and performance visualization.

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1. Sustainability Scores by Material

Each material was evaluated across four primary indicators: Global Warming Potential (GWP), embodied energy, recyclability, and resource efficiency. Scores for each indicator were normalized using the min-max method, ensuring that higher scores represent superior environmental performance (i.e., lower impacts or higher benefits).

Material	GWP Score	Embodied Energy	Recyclability Score	Resource Efficiency	Composite Score (0–10)

		Score		Score	
Bamboo	9.2	9.5	8.3	9.0	**9.0**
Bio-Based Composites	8.8	8.9	7.9	9.4	**9.0**
Recycled Steel	7.1	6.8	9.6	6.5	**7.5**
Geopolymer Concrete	6.7	6.3	5.4	6.0	**6.1**
Portland Cement Concrete	3.2	3.0	2.1	3.5	**2.9**
Virgin Structural Steel	2.5	2.3	4.0	3.0	**2.9**

Key insights:

- **Bamboo and bio-based composites** emerged as the top performers overall, each achieving a composite score of 9.0. These materials excel in carbon sequestration, low embodied energy, and renewable resource usage.
- **Recycled steel** showed the highest recyclability but moderate scores in energy and resource efficiency.
- **Geopolymer concrete** performed better than conventional concrete but lower than other alternatives due to variable curing energy and moderate recyclability.
- Baseline materials (Portland cement and virgin steel) had the lowest composite scores, reaffirming their high environmental burdens.

2. Comparative Ranking

Based on the composite scores, the materials were ranked in terms of overall sustainability:

1.Bamboo
2.BioBased-Composites
3.Recycle-Steel
4.Geopolymer-Concrete
5.Portland-Cement-Concrete
6. Virgin Structural Steel

This ranking highlights the value of integrating renewable and recycled materials in structural design for enhanced sustainability outcomes. The ranking also supports early design-phase material substitution decisions in green buildings.

3. Multi-Criteria Performance Visualization

To visually compare the performance of materials across all indicators, radar diagrams and a ranking bar chart were generated.Each material's relative score is plotted across the four dimensions:

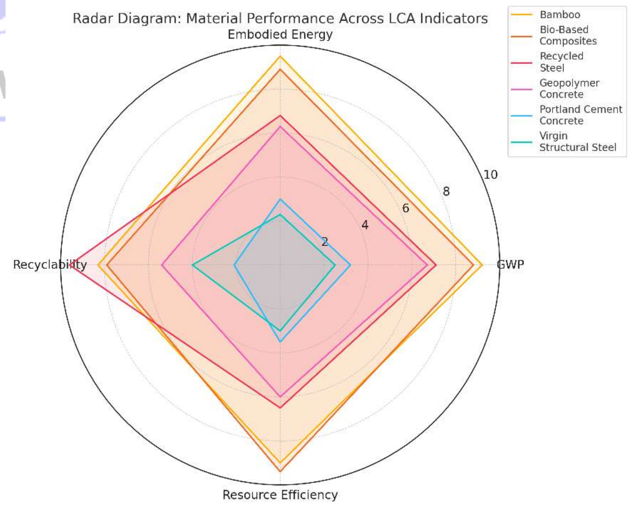
- Bamboo and bio-based composites form nearly full polygons, indicating strength in all categories.
- Recycled steel shows a narrow but tall profile with peak recyclability.
- Portland cement and virgin steel occupy the smallest area, indicating overall poor sustainability performance.

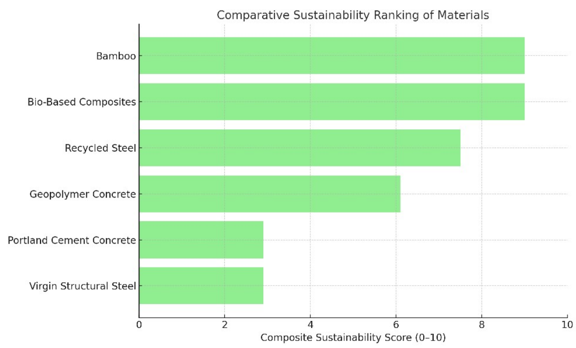
A horizontal bar chart ranks all six materials by their composite sustainability score (0–10 scale), reinforcing the leading position of bamboo and composites, and visually emphasizing the gap between low-carbon and conventional options.

Interpretation of Results

The composite evaluation reinforces the hypothesis that integrating LCA indicators with green certification criteria offers a clearer understanding of material-level sustainability. While traditional materials lag in all categories, newer alternatives such as bamboo and hempcrete not only reduce carbon emissions but also contribute positively toward LEED and BREEAM scoring. The results emphasize the need to prioritize circularity, renewability, and embodied energy reduction in material selection for sustainable construction practices.

These findings serve as a foundation for the discussion section, where certification implications and policy recommendations will be addressed.





Discussion

The findings of this study highlight the complex yet critical relationship between environmental performance, material selection, and green certification outcomes. By integrating LCA indicators with the criteria used in LEED and BREEAM frameworks, this research provides a more structured and quantifiable basis for evaluating sustainability in structural materials. The composite scores not only offer comparative insights into material impacts but also help bridge the technical and practical gap between scientific assessment and certification compliance.

Performance of Materials in Certification Context

From the perspective of green building certification, materials that align with multiple credit categories tend to exhibit stronger sustainability profiles. Bamboo and bio-based composites achieved the highest composite scores due to their low embodied carbon, renewable sourcing, and strong alignment with LEED's *Building Life-Cycle Impact Reduction* and *EPD* credits, as well as BREEAM's *Mat 01* and *Mat 03* categories. These materials inherently support both performance-based and disclosure-based certification requirements.

Recycled steel, while not as low in embodied energy, performs exceptionally well in terms of recyclability and circularity, making it particularly relevant for credits linked to responsible sourcing and waste reduction. Although geopolymer concrete did not score as high overall, its performance in reducing global warming potential compared to traditional concrete suggests significant potential for improvement with further material optimization and standardization.

Conversely, Portland cement concrete and virgin structural steel consistently scored the lowest due to their high energy demands and limited circularity, reaffirming their unsuitability for projects aiming to achieve advanced sustainability ratings under LEED or BREEAM.

Role of Multi-Criteria Decision-Making

The use of a multi-criteria decision-making (MCDM) approach in this study underscores the importance of balancing diverse performance dimensions when evaluating material sustainability. Single-indicator assessments—such as those focusing solely on carbon emissions—can overlook critical trade-offs, such as those between recyclability and embodied energy. By applying a scoring system that aggregates LCA indicators and maps them to certification criteria, designers and engineers are better equipped to make holistic and evidence-based choices. This integrative method allows for more transparent comparisons and supports early-phase decision-making in green building design, where the potential to reduce environmental impact is most significant.

Policy and Procurement Implications

The insights from this research extend beyond design decisions and into broader policy and procurement strategies. Governments and institutional clients increasingly require green certification for public buildings, and tools that quantify material sustainability in alignment with certification systems can guide incentive structures, product labeling, and procurement criteria. For example, public procurement policies could prioritize materials that meet a minimum composite sustainability score, thereby driving market demand toward environmentally preferable options.

Moreover, manufacturers and suppliers could benefit from understanding how their products perform not just in isolation, but within the multi-indicator frameworks valued by certification systems. This could lead to more targeted Environmental Product Declarations (EPDs), investment in lower-carbon production processes, and innovations in recyclable material design.

Methodological Limitations

Despite its strengths, the methodology presented in this study is subject to certain limitations. One of the primary challenges is the availability and consistency of Environmental Product Declarations (EPDs) across regions and material categories. Many low-carbon or innovative materials, such as hempcrete or geopolymer binders, lack standardized or regionally specific EPDs, making it difficult to ensure uniform data quality. Additionally, regional variations in electricity mix, transportation infrastructure, and manufacturing practices can significantly affect LCA outcomes, potentially leading to different results in different contexts.

Another limitation involves the weighting scheme used in the composite scoring process. While a combination of literature-based and stakeholder-informed weights enhances objectivity, preferences can still vary depending on project goals, building typology, or geographic regulations. Future work may benefit from dynamic weighting models that allow for customization based on context-specific priorities.

Conclusion

This study presents an integrated, multi-criteria approach to evaluating the sustainability of structural materials, bridging the gap between scientific life cycle analysis and practical certification frameworks such as LEED and BREEAM. By aligning key LCA indicators—such as global warming potential, embodied energy, recyclability, and resource efficiency—with green building credit categories, a standardized scoring matrix was developed to assess and rank materials in a manner both scientifically robust and practically relevant.

The findings reveal that bamboo and bio-based composites consistently demonstrate superior performance across most indicators, making them highly suitable for integration into green building projects targeting advanced sustainability certification. Their renewable origin, low embodied energy, and alignment with life-cycle impact reduction criteria position them as leading candidates for future sustainable construction practices. Recycled steel, while not as strong in energy performance, offers unmatched value in terms of circularity and end-of-life recovery, supporting responsible sourcing and material reuse goals.

These results underscore the need for more data-driven, transparent, and standardized tools to support material selection during early design phases. By translating environmental performance into actionable sustainability scores, this model empowers architects, engineers, and policy stakeholders to make informed decisions that align with certification goals and climate-resilient construction standards.

Moving forward, it is recommended that green building initiatives:

- Encourage the use of multi-criteria scoring tools in material procurement and design evaluation;
- Promote greater transparency through expanded access to verified EPDs for emerging materials;
- Integrate region-specific LCA databases to improve contextual accuracy in sustainability assessments;

- Incentivize manufacturers to improve material performance by linking procurement to certification-aligned benchmarks.

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