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Comparative Life Cycle Carbon Footprint of Geopolymer Concrete, Bamboo, Recycled Steel, and Bio-Based Composites: Towards Decarbonizing Structural Materials

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Abstract

The construction industry is among the largest contributors to anthropogenic greenhouse gas emissions, with cement and steel production alone accounting for a significant share of global embodied carbon in the built environment. As decarbonization becomes a critical priority, there is an urgent need to explore and validate alternative structural materials that can reduce lifecycle emissions without compromising performance. This study conducts a comparative cradle-to-grave carbon footprint assessment of four emerging low-carbon materials—geopolymer concrete, bamboo, recycled steel, and bio-based composites—benchmarking their performance against conventional Portland cement concrete and virgin structural steel. Using ISO-compliant Life Cycle Assessment (LCA) methods and a consistent functional unit of 1 m³, the analysis reveals that geopolymer concrete achieves a 35–45 % reduction in Global Warming Potential (GWP) relative to conventional concrete, while bamboo and bio-based composites exhibit even greater reductions, ranging between 60–80 %. Recycled steel also demonstrates a notable decrease in embodied emissions—approximately 40–50 % compared to virgin steel—owing to lower energy requirements in secondary production. These findings underscore the substantial climate benefits of substituting high-impact conventional materials with low-carbon alternatives. The study provides evidence-based insights to guide engineers, designers, and policymakers in material selection strategies that align with net-zero targets and accelerate the transition toward a low-emission-built environment.

Keywords

Low-carbon materials, Carbon footprint, Geopolymer concrete, Bamboo, Recycled steel, Bio-based composites, Embodied carbon

1. Introduction

The construction sector is a cornerstone of economic development and urbanization, yet it also represents one of the most carbons-intensive industries globally. Estimates suggest that the building and construction value chain accounts for nearly 39 % of global energy-related CO_2 emissions, with embodied emissions from material production forming a significant portion of this footprint. Among structural materials, cement and steel dominate both in use and in climate impact. Cement production alone contributes approximately 5–8 % of total global CO_2 emissions, primarily due to the calcination of limestone and the heavy energy inputs required in clinker production. Similarly, steel manufacturing accounts for 7–9 % of global emissions, with the blast furnace–basic oxygen furnace route being particularly energy- and carbon-intensive. The widespread reliance on these materials in buildings and infrastructure continues to pose a challenge to achieving climate targets such as those outlined in the Paris Agreement.

Despite ongoing technological improvements, conventional concrete and steel remain fundamentally limited in their ability to deliver low-carbon outcomes. Portland cement-based concrete is highly carbon-emissive due to the inherent process emissions associated with clinker production, while structural steel depends on energy-intensive extraction and smelting processes, often powered by fossil-fuel-dominated grids. These materials also offer limited circularity in practice, with recycling processes for steel often constrained by quality considerations and concrete recycling largely down-cycled into non-structural applications. While efforts such as clinker substitution and electric arc furnace steelmaking have shown progress, they fall short of the deep decarbonization urgently needed in the sector.

Emerging low-carbon alternatives—such as geopolymer concrete, bamboo, recycled steel, and bio-based composites—present promising pathways to reduce embodied emissions. However, their integration into mainstream construction remains slow, partly due to the lack of consolidated and comparable carbon data. Existing research often focuses on single materials, isolated life cycle stages, or region-specific case studies, limiting its applicability in comparative decision-making. A comprehensive and standardized evaluation that examines these alternatives against conventional baselines across their full life cycle is critically lacking.

2. Literature Review

The environmental burden of construction materials has been widely investigated, with Life Cycle Assessment (LCA) emerging as the most robust framework for quantifying embodied impacts. Previous studies consistently highlight those traditional materials such as cement and steel are among the largest contributors to the carbon footprint of buildings and infrastructure. Ghanbari (2023) demonstrated through an LCA of 22 building materials that aluminum, cement, and steel exhibit some of the highest embodied energy and emissions, reinforcing concerns over their unsustainable production pathways. Similarly, Rissman et al. (2020) and De Ras et al. (2019) emphasized that steelmaking alone contributes between 7–9 % of global CO_2 emissions, while Portland cement production accounts for an additional 5–8 %, largely due to the calcination process and fossil-fuel-intensive kilns.

In response, growing attention has been directed toward low-carbon alternatives. Geopolymer concrete, derived from industrial by-products such as fly ash and slag, has been shown to achieve 35–45 % lower Global Warming Potential (GWP) than conventional cement concrete (Thorne et al., 2024). Studies by Maddalena et al. (2018) and Salas et al. (2018) also note that geopolymer systems can maintain comparable structural performance while substantially reducing clinker dependency. In parallel, natural materials like bamboo have emerged as renewable structural options. Rettinger and Meyer (2023) explored material selection frameworks for low-carbon design, emphasizing bamboo's rapid renewability, carbon sequestration capacity, and favorable strength-to-weight ratio, though they acknowledged challenges in durability and standardization.

Recycled steel also features prominently in the decarbonization discourse. Allan and Phillips (2021) reported that substituting virgin steel with recycled steel in structural applications can lower embodied carbon by up to 50 %, particularly when electric arc furnace (EAF) routes are used. These findings align with Hart et al. (2021), who demonstrated that mass-recycled steel and engineered timber can significantly reduce whole-life embodied carbon in multistory buildings. Bio-based composites such as hempcrete and natural fiber-reinforced binders have additionally attracted interest for their biogenic carbon storage and low-energy manufacturing processes (Tokede et al., 2022).

Despite this promising body of work, several gaps remain. Cabeza et al. (2020) highlighted the lack of harmonized LCA methodologies, noting that inconsistent system boundaries and data quality issues hinder meaningful comparisons across studies. Furthermore, most research isolates a single material or impact category, offering limited insights for multi-criteria decision-making in real-world design contexts. Caruso et al. (2017) argued for the integration of sustainability indicators within early-stage design frameworks, while Tokede et al. (2022) called for combined assessments that include environmental, economic, and social dimensions.

Taken together, the literature underscores two critical needs: first, a standardized, cradle-to-grave comparison of emerging low-carbon structural materials against conventional benchmarks, and second, the translation of these findings into actionable tools for designers and policymakers. This study responds to these needs by providing a consolidated comparative LCA of geopolymer concrete, bamboo, recycled steel, and bio-based composites, situating their environmental performance within the broader context of decarbonizing the built environment.

3. Methodology

This study adopts a comparative Life Cycle Assessment (LCA) framework to evaluate the carbon performance of emerging low-carbon structural materials in relation to conventional construction options. The approach aligns with the guidelines set out in ISO 14040 and ISO 14044, ensuring transparency, reproducibility, and methodological consistency across all assessed materials.

3.1 Material Selection

The materials chosen for this study reflect a balance between structural relevance, market availability, and potential for emission reduction. Four low-carbon alternatives—geopolymer concrete, bamboo, recycled structural steel, and bio-based composites—were selected due to their growing prominence in sustainability research and their capacity to serve as viable substitutes for conventional construction materials. For benchmarking purposes, two conventional materials, Portland cement-based concrete and virgin structural steel, were included as baseline references. These baselines represent current industry norms and allow for a meaningful comparison of potential carbon savings offered by the alternatives.

3.2 System Boundaries

The assessment was conducted using cradle-to-grave system boundaries. This encompasses all life cycle stages of each material, including raw material extraction, manufacturing and processing, transportation to the construction site, installation, and end-of-life management (e.g., recycling, reuse, or disposal). This boundary choice ensures that the full spectrum of embodied carbon emissions is captured and avoids underestimating the impacts of downstream processes, which are often overlooked in partial assessments.

3.3 Functional Unit

To maintain comparability across materials with differing densities and structural properties, a functional unit of **1 m³ of material** was adopted. This volumetric basis is consistent with previous construction LCA studies and allows for the direct comparison of emission intensities per unit of material used, independent of application-specific variations.

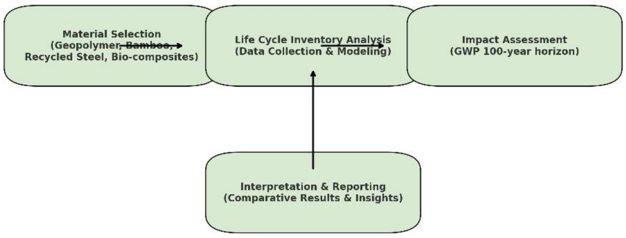
3.4 LCA Tools and Databases

The environmental modeling was conducted using SimaPro and GaBi—two widely recognized LCA software platforms. Background life cycle inventory (LCI) data were sourced primarily from the Ecoinvent database, supplemented with manufacturer-specific Environmental Product Declarations (EPDs) and peer-reviewed literature where necessary. These sources were chosen for their methodological rigor, regional adaptability, and detailed documentation of material flows.

3.5 Impact Category

The study focused on **Global Warming Potential (GWP)** as the primary impact category, expressed in kilograms of CO_2-equivalent (kg CO_2e) per cubic meter of material. A 100-year time horizon (GWP100), as recommended by the Intergovernmental Panel on Climate Change (IPCC), was applied to ensure consistency with international climate reporting standards.

Figure 1. Life Cycle Assessment (LCA) Methodology Framework



5. Results

This section presents the findings of the comparative Life Cycle Assessment (LCA), focusing on the total carbon footprint of the assessed materials, emissions distribution across life cycle stages, and their relative ranking based on Global Warming Potential (GWP). All results are reported per the functional unit of 1 m³ of material.

5.1 Total Carbon Footprint

The comparative LCA results reveal substantial differences in cradle-to-grave carbon emissions across the materials studied. As expected, the conventional materials—Portland cement concrete and virgin structural steel—exhibit the highest embodied carbon. Portland cement concrete recorded a GWP range of 370–450 kg CO_2e/m^3, driven largely by process emissions during clinker production. Virgin structural steel showed the greatest carbon intensity, with values ranging from 850–950 kg CO_2e/m^3, reflecting the energy demands of blast furnace–basic oxygen furnace (BF-BOF) steelmaking.

In contrast, the low-carbon alternatives demonstrated marked reductions in GWP. Geopolymer concrete achieved a GWP of 230–280 kg CO_2e/m^3, representing a 35–45 % decrease relative to conventional concrete. Bamboo, due to its biogenic carbon storage and minimal processing requirements, exhibited the lowest footprint, at 90–150 kg CO_2e/m^3—a reduction of up to 75 % compared to concrete. Bio-based composites (e.g., hempcrete) also performed favorably, with values between 120–180 kg CO_2e/m^3, while recycled steel significantly improved on its virgin counterpart, showing 450–550 kg CO_2e/m^3 (a 40–50 % reduction).

5.2 Emissions Breakdown by Life Cycle Stage

Figure 2 provides a breakdown of emissions across the key life cycle phases (A1–C4) for each material.

- **Production phase (A1–A3):** This stage was the dominant contributor for all materials, accounting for more than 70 % of total emissions in concrete and steel. For cement-based concrete, clinker production was the primary hotspot, while for steel, ore extraction and smelting dominated emissions. In contrast, geopolymer concrete shifted some emissions to activator production and curing processes, though still maintaining a lower overall GWP.
- **Transportation and construction (A4–A5):** Transport-related emissions varied significantly by material density. Bamboo and bio-based composites exhibited minimal impacts in this stage due to their lightweight nature and potential for local sourcing, whereas steel and conventional concrete incurred higher transportation-related emissions.
- **End-of-life (C1–C4):** Recycled steel benefited from high recovery rates (exceeding 90 %), yielding notable impact offsets. Conversely, concrete's end-of-life emissions were higher due to limited reuse

potential and energy requirements for crushing and disposal. Bio-based composites displayed modest end-of-life emissions, reflecting biodegradability and low-energy disposal processes.

5.3 Comparative Ranking of Materials

Based on total GWP values, the materials were ranked as follows (from lowest to highest):

1. **Bamboo** (90–150 kg CO_2e/m^3)
2. **Bio-based composites** (120–180 kg CO_2e/m^3)
3. **Geopolymer concrete** (230–280 kg CO_2e/m^3)
4. **Recycled steel** (450–550 kg CO_2e/m^3)
5. **Portland cement concrete** (370–450 kg CO_2e/m^3)
6. **Virgin structural steel** (850–950 kg CO_2e/m^3)

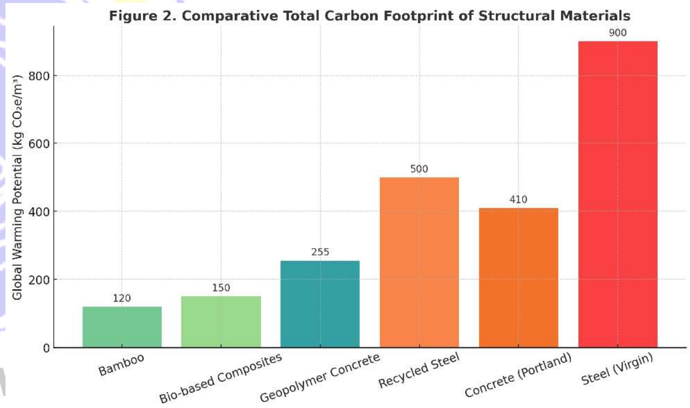
This ranking highlights the significant potential of bio-based and geopolymer alternatives to lower embodied carbon, while recycled steel offers a pragmatic improvement pathway for high-strength applications requiring metallic components.

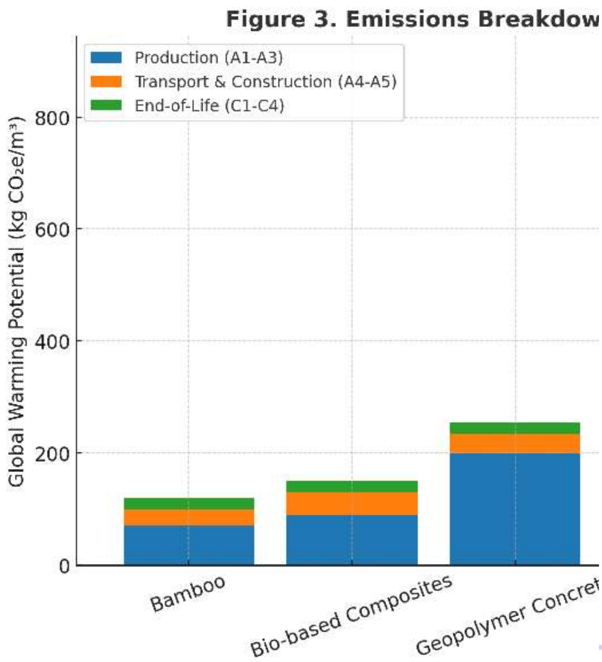
5.4 Graphical Representation

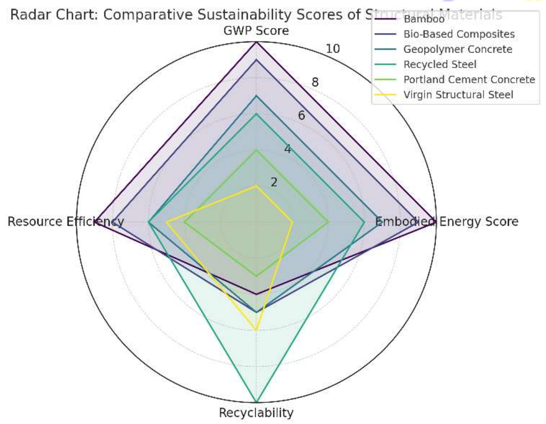
To enhance interpretability, the results are visually summarized:

- Figure 2 presents a bar chart comparing total GWP (kg CO_2e/m^3) for all materials.
- Figure 3 provides a stacked column chart showing the distribution of emissions across life cycle stages (A1–C4).

These visualizations reinforce that bamboo and bio-based composites are the most climate-favorable options, while virgin steel remains the most carbon-intensive, even when full end-of-life recovery is considered.







6. Discussion

6.1 Hotspot Analysis

The LCA results reveal that the production phase (A1–A3) dominates total carbon emissions for all studied materials, particularly for Portland cement concrete and virgin steel. In conventional concrete, clinker production remains the single largest hotspot, responsible for over 70 % of total GWP due to calcination and high-temperature kiln operations. Similarly, blast furnace–basic oxygen furnace (BF-BOF) steelmaking accounted for the majority of emissions in virgin steel, driven by fossil-fuel-based energy use and the carbon-intensive nature of iron ore reduction. In comparison, geopolymer concrete exhibited a shift in emissions profile, with a notable share attributable to alkali activator production, though overall emissions were significantly lower than its Portland counterpart. Bamboo and bio-based composites showed a markedly different distribution, with relatively low production emissions offset partially by transportation and processing stages, highlighting their potential when sourced and processed loacally.

6.2 Implications for Material Substitution

The comparative ranking clearly demonstrates that bamboo, bio-based composites, and geopolymer concrete can deliver substantial reductions in embodied carbon, supporting their role as effective substitutes in decarbonization strategies. Substituting Portland cement concrete with geopolymer alternatives could reduce emissions by up to 45 %, while replacing virgin steel with recycled steel offers reductions of approximately 50 %. Bamboo, in particular, offers a compelling case for structural and non-structural applications in regions where it is abundant, providing both carbon sequestration benefits and low processing emissions. These findings align with emerging net-zero roadmaps, where material substitution is identified as a key lever for achieving sectoral emission targets.

6.3 Contextual Applicability

While the results are globally relevant, regional supply chains and material availability significantly influence their practical applicability. Geopolymer concrete depends on the availability of industrial by-products such as fly ash and slag, which vary across regions due to changing energy and manufacturing profiles. Bamboo's benefits are maximized when sourced from areas where it grows natively, reducing transportation emissions and supporting local economies. Likewise, the carbon advantage of recycled steel is contingent upon access to high-efficiency electric arc furnaces and a reliable scrap supply chain. Therefore, material selection should be context-specific, informed by local infrastructure, policy frameworks, and economic considerations.

6.4 Limitations

This study, while comprehensive, is not without limitations. The results are influenced by data variability in life cycle inventories, particularly for emerging materials such as bio-based composites, where standardized Environmental Product Declarations (EPDs) are limited. Regional assumptions regarding energy mixes, transportation distances, and end-of-life scenarios introduce additional uncertainties. Furthermore, only Global Warming Potential was assessed, whereas a full sustainability evaluation would require considering other impact categories such as resource depletion, water use, and social implications. Future research should aim to incorporate multi-criteria assessments and region-specific datasets to refine the robustness of these findings.

7. Conclusion

This study conducted a cradle-to-grave Life Cycle Assessment of four emerging low-carbon structural materials—geopolymer concrete, bamboo, recycled steel, and bio-based composites—benchmarking their performance against conventional Portland cement concrete and virgin structural steel. The findings reveal that geopolymer concrete achieves a 35–45 % reduction in Global Warming Potential (GWP) relative to conventional concrete, while bamboo and bio-based composites offer reductions of up to 70–75 % due to their low processing requirements and carbon sequestration potential. Recycled steel demonstrated a

40–50 % decrease in embodied emissions compared to virgin steel, highlighting the critical role of circular material flows in reducing the climate burden of structural metals.

These results underscore the transformative potential of material substitution in decarbonizing the built environment. Policy frameworks should incentivize the integration of low-carbon materials by expanding green building codes, introducing tax benefits for low-emission products, and encouraging regional supply chain development to support the local sourcing of bamboo, recycled steel, and industrial by-products for geopolymer production. For practitioners, the findings provide actionable insights to guide sustainable material selection in early-stage design, aligning project delivery with net-zero and green certification goals.

By quantifying the comparative advantages of these alternatives, this study contributes evidence-based data to the global discourse on sustainable construction. Future work should integrate additional environmental and socio-economic indicators to provide a more holistic view of material sustainability and strengthen the case for their widespread adoption.

References

- Allan, K., & Phillips, A. (2021). Comparative cradle-to-grave life cycle assessment of low and mid-rise mass timber buildings with equivalent structural steel alternatives. *Sustainability*, 13(6), 3401. https://doi.org/10.3390/SU13063401
- 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*, e02326. https://doi.org/10.1016/j.cscm.2023.e02326
- Cabeza, L., Boquera, L., Chàfer, M., & Vérez, D. (2020). Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis. *Energy and Buildings*, 110612. https://doi.org/10.1016/j.enbuild.2020.110612
- Caruso, M., Menna, C., Asprone, D., Prota, A., & Manfredi, G. (2017). Methodology for life-cycle sustainability assessment of building structures. *ACI Structural*

Journal. https://doi.org/10.14359/51689426

- Chen, Z., Gu, H., Bergman, R., & Liang, S. (2020). Comparative life-cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the Athena Impact Estimator for Buildings. *Sustainability*, 12(11), 4708. https://doi.org/10.3390/su12114708
- De Ras, K., Van De Vijver, R., Galvita, V. G., Marin, G. B., & Van Geem, M. K. (2019). Carbon capture and utilization in the steel industry: Challenges and opportunities. *Current Opinion in Chemical Engineering*.
- Farooq, F., Jin, X., Javed, M. F., Akbar, A., & Shah, M. I. (2021). Geopolymer concrete as sustainable material: A state of the art review. *Construction and Building Materials*.
- Ghanbari, M. (2023). Environmental impact assessment of building materials using life cycle assessment. *Journal of Architecture and Environmental Sustainability Research*. https://doi.org/10.30564/jaeser.v6i4.5964
- Hart, J., D'Amico, B., & Pomponi, F. (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology*, 25(6), 13139. https://doi.org/10.1111/jiec.13139
- Hasanbeigi, A., et al. (2010). International benchmarking of energy intensity and CO_2 emissions in the cement industry. *Global Efficiency Intelligence*.
- IEA. (2020). Global emissions from cement production. *International Energy Agency*.
- Maddalena, R., et al. (2018). Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Technologies and Environmental Policy*.