



QUANTIFYING THE NET CARBON PERFORMANCE OF A BAMBOO HALL IN MALAYSIA USING LIFECYCLE ANALYSIS

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Abstract

The construction sector contributes significantly to global greenhouse gas emissions, increasing demand for low-carbon building materials and lifecycle-based assessment approaches. This study quantifies the net carbon performance of a bamboo hall in Ipoh, Malaysia, using a lifecycle carbon assessment framework integrating carbon sequestration, embodied carbon, and operational carbon emissions. The functional unit was one completed bamboo hall with a total construction volume of 90 m³ over a 30-year service life. The system boundary included bamboo growth, harvesting, treatment, transportation, installation, and operational electricity use. A three-phase methodology was employed. Phase 1 estimated carbon sequestration potential of four bamboo species using the LICOR6400XT Portable Photosynthesis System. Phase 2 quantified embodied carbon emissions from harvesting, processing, transportation, and installation activities. Phase 3 projected operational carbon emissions based on electricity consumption assumptions and Malaysia's 2025 grid emission factor. Results showed that the bamboo hall sequestered 178,548 kg CO₂e, while embodied and operational emissions totalled 19,207.1 kg CO₂e over the 30-year lifecycle. The resulting net carbon balance was -159,340.9 kg CO₂e, indicating that carbon sequestration was approximately 9.3 times greater than total lifecycle emissions under the defined assumptions. These findings demonstrate the potential of bamboo construction as a nature-based solution for climate mitigation.

Keywords: Bamboo Construction, Lifecycle Carbon Assessment, Embodied Carbon, Biogenic Carbon Storage, Carbon Sequestration, Nature-Based Solutions

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INTRODUCTION

The construction sector is a major contributor to global greenhouse gas emissions due to the extensive use of carbon-intensive materials such as concrete and steel. The United Nations Environment Programme (UNEP, 2023) reported that the building sector accounts for approximately 37% of global carbon emissions, with a significant proportion originating from material production and building operations. As climate mitigation becomes a priority in urban development, increasing attention has been directed towards sustainable construction approaches and low-carbon building materials (Kibert, 2022).

Bamboo has emerged as a promising alternative construction material because of its rapid growth rate, renewability, and high carbon sequestration potential. Compared with conventional materials, bamboo requires lower processing energy and can store substantial amounts of atmospheric carbon during its growth phase (Lobovikov et al., 2005; Xu et al., 2022). In tropical regions such as Malaysia, bamboo also offers advantages in terms of local availability, fast regeneration, and suitability for climate-responsive architecture. Previous studies have highlighted bamboo's environmental and structural potential in sustainable construction applications (Boity et al., 2022; Hildayanti & Wasilah, 2023).

Despite growing interest in bamboo construction, important methodological gaps remain in evaluating its net carbon performance at the building scale. Existing studies primarily focus on either biomass sequestration or embodied carbon independently, while limited research integrates carbon sequestration, embodied carbon emissions, and operational emissions within a unified lifecycle assessment framework (Xu et al., 2022). In addition, inconsistencies in functional units, system boundaries, and carbon reporting methods make comparisons between studies difficult and limit practical application in planning and construction decision-making processes.

For planners, architects, and local authorities, understanding the lifecycle carbon implications of bamboo construction is important for developing evidence-based low-carbon building strategies, material procurement policies, and sustainable urban development guidelines. Quantifying the net carbon performance of bamboo structures can support more informed decisions regarding local sourcing, transportation distance, operational efficiency, and material selection in future development projects.

Therefore, this study quantifies the net carbon performance of a bamboo hall in Ipoh, Malaysia, using a lifecycle carbon assessment framework integrating carbon sequestration, embodied carbon, and operational emissions over a 30-year service life. The study aims to: (i) quantify the carbon sequestration potential of selected bamboo species, (ii) evaluate embodied carbon emissions associated with bamboo harvesting, treatment, transportation, and installation, and (iii)

assess operational carbon emissions during building use. This study contributes a building-scale lifecycle carbon assessment framework for bamboo construction in tropical urban environments and provides planner-oriented insights for low-carbon development strategies.

LITERATURE REVIEW AND RESEARCH GAPS

Previous studies have highlighted bamboo's potential as a sustainable construction material due to its rapid growth rate, renewability, and capacity to sequester atmospheric carbon. Lobovikov et al. (2005) reported that bamboo can store substantial amounts of carbon because of its fast biomass accumulation, while Xu et al. (2022) demonstrated bamboo's potential to reduce lifecycle carbon emissions when used as a construction material. Other studies have emphasised bamboo's structural, environmental, and architectural advantages in sustainable building applications (Boity et al., 2022; Hildayanti & Wasilah, 2023). However, most existing research focuses primarily on material properties, general sustainability performance, or carbon sequestration potential without evaluating the complete lifecycle carbon implications at the building scale.

Table 1: Summaries of selected studies related to bamboo construction and lifecycle carbon assessment.

Study	Focus	Limitation
Lobovikov et al. (2005)	Bamboo carbon sequestration	No building-scale lifecycle assessment
Boity et al. (2022)	Sustainable bamboo construction	Limited carbon quantification
Hildayanti & Wasilah (2023)	Bamboo as alternative building material	No lifecycle carbon analysis
Xu et al. (2022)	Bamboo carbon storage and emission reduction	Limited operational carbon assessment

Despite growing interest in low-carbon construction materials, limited studies have integrated carbon sequestration, embodied carbon emissions, and operational carbon emissions within a unified lifecycle assessment framework for real-world bamboo buildings in tropical urban contexts. Furthermore, there remains limited evidence regarding how local sourcing, transportation distance, operational energy use, and bamboo species selection influence overall net carbon performance. Therefore, this study addresses these gaps by quantifying the net carbon performance of a bamboo hall in Ipoh, Malaysia, using a lifecycle carbon assessment framework integrating sequestration, embodied carbon, and operational emissions over a 30-year service life.

METHODOLOGY

This study employed a lifecycle carbon assessment approach to quantify the net carbon performance of a bamboo hall located in Ipoh, Malaysia. The assessment

integrated carbon sequestration, embodied carbon emissions, and operational carbon emissions over the building lifecycle. The methodology was adapted from Xu et al. (2022) and refined to suit tropical bamboo construction conditions and locally sourced bamboo materials.

Functional Unit and System Boundary

The functional unit adopted in this study was one completed bamboo hall with a total construction volume of 90 m³ (Figure 1) and an assumed service life of 30 years. Carbon performance was evaluated based on the total carbon sequestration and lifecycle emissions associated with the building throughout the defined assessment period.

The system boundary included bamboo growth and carbon sequestration, harvesting, treatment and manufacturing, transportation, installation, and operational energy use during the building lifespan. Operational assessment considered electricity consumption from lighting, ceiling fans, and plug points. The study excluded emissions associated with foundation construction, human labour, maintenance and replacement activities, demolition processes, and end-of-life carbon release scenarios. Carbon values expressed as elemental carbon (C) were converted into carbon dioxide equivalent (CO₂e) using the molecular ratio of 44/12 to ensure consistency in lifecycle carbon reporting.

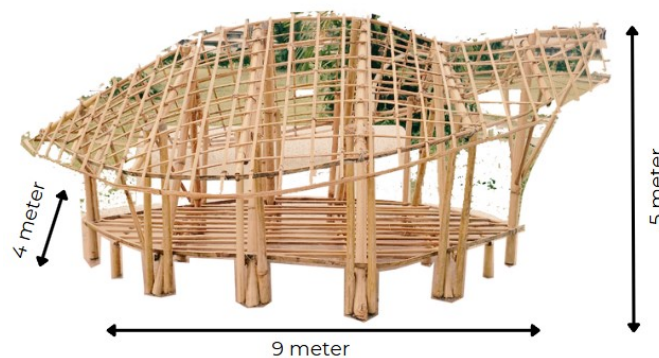


Figure 1: Bamboo Hall Geometry with Estimated Construction Volume Of 90 M³

Lifecycle Carbon Assessment Framework

The lifecycle carbon assessment framework consisted of three phases: (i) quantification of bamboo carbon sequestration potential, (ii) assessment of embodied carbon emissions associated with harvesting, processing, transportation, and installation, and (iii) evaluation of operational carbon emissions during building use. The overall net carbon balance was calculated as total lifecycle emissions minus total carbon sequestration, where negative values

indicate that sequestration exceeds emissions. Figure 2 presents the lifecycle carbon assessment framework, illustrating the relationship between carbon sequestration, embodied carbon emissions, operational carbon emissions, and the resulting net carbon balance.

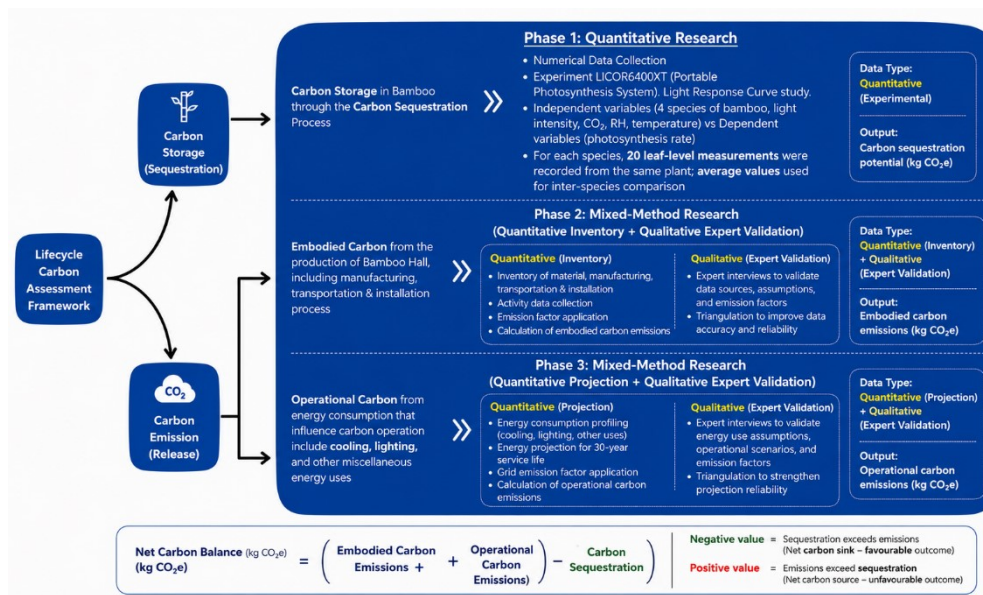


Figure 2: Lifecycle carbon assessment framework for quantifying the net carbon performance of the bamboo hall.

Phase 1: Carbon Sequestration Assessment

Phase 1 quantified the carbon sequestration potential of bamboo species used in the construction of the bamboo hall. Four bamboo species commonly applied in the project were assessed: *Dendrocalamus asper* (betung), *Gigantochloa scortechinii* (semantan), *Gigantochloa albociliata* (madu), and *Schizostachyum brachycladum* (lemang).

Carbon sequestration potential was estimated through photosynthetic performance measurement using the LICOR6400XT Portable Photosynthesis System under controlled environmental conditions. A light response curve experiment was conducted to evaluate photosynthetic assimilation rates under varying photosynthetically active radiation (PAR) levels, with controlled light intensity, CO₂ concentration, relative humidity, and temperature. The dependent variable was the net photosynthetic assimilation rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

For each bamboo species, 20 leaf-level measurements were recorded from a representative mature plant under controlled conditions. Measured

assimilation rates were converted into estimated annual carbon sequestration values using species-specific canopy area and leaf area index data, and molecular carbon conversion assumptions. This phase was intended to estimate comparative carbon sequestration potential rather than direct long-term carbon storage in harvested structural bamboo.

Phase 2: Embodied Carbon Assessment

Phase 2 quantified embodied carbon emissions associated with bamboo harvesting, processing, transportation, and installation for the bamboo hall construction. The assessment adopted an inventory-based calculation approach using activity data collected from actual construction processes and validated through consultation with a subject matter expert involved in the project. All bamboo was harvested in Perak only, supporting bamboo as locally sourced.

The embodied carbon boundary included three stages: (i) bamboo harvesting and preliminary processing (frontend operations), (ii) workshop treatment and fabrication (backend processing), and (iii) transportation and on-site bamboo installation activities.

Harvesting emissions were calculated based on energy consumption from equipment used during bamboo extraction, including pole saws, chainsaws, grass cutters, grinders, and generators. Workshop processing emissions included bamboo splitting, washing, preservative treatment, drying-related activities, and fabrication using electrical tools. Transportation emissions were calculated using actual travel distances between bamboo sourcing locations, processing sites, and the construction site, considering vehicle type, fuel consumption rates, and corresponding fuel emission factors. Vehicle categories included diesel lorries, sport utility vehicles, and motorcycles, reflecting actual project logistics. Installation emissions were estimated based on electricity consumption from tools used during on site bamboo assembly, including hand drills, air compressors, and grinders. Carbon emissions were calculated using Malaysia's 2025 electricity grid emission factor.

Embodied carbon emissions were expressed in kg CO₂e and aggregated across all included inventory stages. Foundation related construction activities, human labour energy expenditure, material wastage, maintenance and replacement, demolition, and end-of-life scenarios were excluded due to boundary limitations and data constraints.

Phase 3: Operational Carbon Assessment

Phase 3 quantified operational carbon emissions associated with electricity consumption during the use phase of the bamboo hall over the assumed 30 years' service life. The assessment adopted a projection based quantitative approach supported by expert consultation to validate operational assumptions.

Operational energy demand included lighting, ceiling fan operation, and plug point electricity use based on the proposed electrical configuration of the bamboo hall. Daily operating assumptions were defined as 12 hours for LED lighting, 8 hours for ceiling fan use, and 4 hours for plug-point electricity use, representing projected typical operational conditions.

Daily electricity consumption was calculated based on equipment power ratings and estimated usage duration. Operational carbon emissions were subsequently calculated using Malaysia's 2025 electricity grid emission factor. Annual operational emissions were projected using a 365-day operating schedule and extrapolated across the 30 years' service life. Operational carbon emissions were expressed in kg CO₂e and incorporated into the overall net carbon balance calculation.

RESULTS AND DISCUSSION

Phase 1: Carbon Sequestration Potential and Structural Carbon Storage

Phase 1 evaluated the carbon sequestration potential of four bamboo species used in the construction of the bamboo hall based on photosynthetic performance under controlled environmental conditions. Light response curve analysis revealed distinct differences in photosynthetic assimilation rates among the species tested (Figure 3). *Gigantochloa scortechinii* (semantan) recorded the highest average net photosynthetic assimilation rate at 8.5 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, followed by *Schizostachyum brachycladum* (lemang) at 6.8 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, *Gigantochloa albociliata* (madu) at 6.0 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, and *Dendrocalamus asper* (betung) at 2.5 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. These findings indicate notable inter-species variation in carbon assimilation performance under identical measurement conditions. These estimates represent comparative biogenic carbon storage potential derived from species-specific physiological performance and structural allocation assumptions, rather than direct destructive biomass carbon quantification.

Differences in canopy characteristics further influenced estimated sequestration potential. As shown in Table 2, *G. scortechinii* exhibited the highest leaf area index (LAI = 5.66) and canopy area (296.65 m²), resulting in the highest estimated annual sequestration potential among the species assessed. Although *G. albociliata* demonstrated a lower assimilation rate than *G. scortechinii*, its estimated carbon storage per culm remained comparatively high due to its structural characteristics. The integration of photosynthetic assimilation rates, canopy area, and leaf area index enabled estimation of species-specific biogenic carbon storage relevant to structural construction applications.

Based on the measured species-specific carbon storage estimates and the quantity of bamboo incorporated into the hall structure, the total estimated biogenic carbon storage potential represented by the bamboo structure was

48,695 kg C, equivalent to 178,548 kg CO₂e. The distribution of stored carbon across structural components is presented in Table 3. Structural elements requiring larger quantities of semantan and madu bamboo contributed the highest carbon storage due to both material volume and species-specific sequestration potential. These findings demonstrate the substantial carbon storage potential of bamboo when utilised as a structural building material. Table 3 shows the specific species conversion of photosynthetic assimilation into estimated carbon storage per bamboo culm, which formed the basis for whole structure carbon accounting.

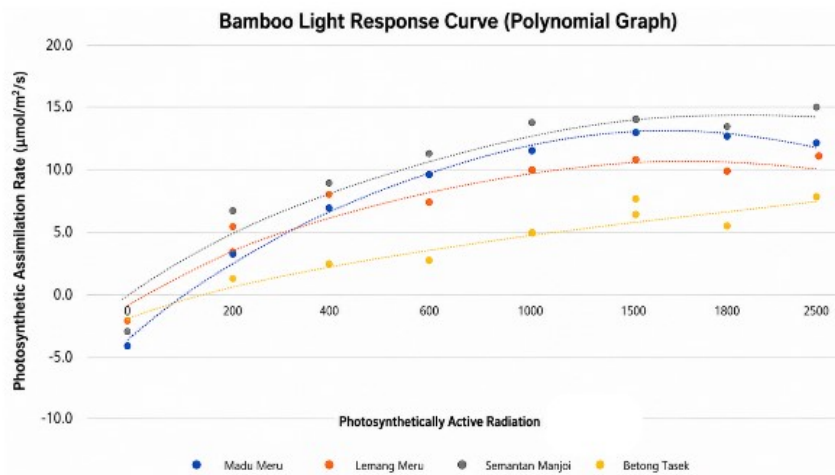


Figure 3: Light response curves showing net photosynthetic assimilation rates of four bamboo species under varying photosynthetically active radiation (PAR) levels.

Table 2: Net photosynthetic assimilation rates of four bamboo species under varying photosynthetically active radiation (PAR)

No	Photosynthetically Active Radiation (PAR) ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Photosynthesis Assimilation Rate ($\mu\text{mol/m}^2/\text{s CO}_2$)			
		Betung	Semantan	Madu	Lemang
1	0	-1.9*	-2.7*	-4.1*	-2.0*
2	200	1.0	6.6	3.3	5.4
3	400	2.0	7.8	8.2	8.2
4	600	2.5	8.8	9.4	7.5
5	1000	4.8	13.9	10.8	10.7
6	1500	6.8	12.9	13.7	8.1
7	1800	5.7	13.6	12.9	9.9
8	2500	8.1	15.1	12.4	11.8
	Average Net Assimilation Rate	2.5	8.5	6.0	6.8

* Negative values at PAR = 0 indicate net carbon loss due to dark respiration.

Table 3: Carbon storage per clump and per culm in four bamboo species

Bamboo Species	Average Net Assimilation Rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	Crown Area (m^2)	Leaf Area Index (LAI)	Estimated Carbon Storage per Culm (kg C)
<i>Dendrocalamus asper</i> (Betung)	2.5	68.98	2.89	142.6
<i>Gigantochloa scortechinii</i> (Semantan)	8.5	296.65	5.66	268.2
<i>Gigantochloa albociliata</i> (Madu)	6.0	51.35	2.08	276.5
<i>Schizostachyum brachycladum</i> (Lemang)	6.8	12.11	3.88	68.6

This study estimated specific species biogenic carbon storage based on measured photosynthetic assimilation rates and structural bamboo allocation within the bamboo hall. Based on the construction inventory, the bamboo hall incorporated structural bamboo components comprising betung for columns, floor beams, and roof trusses; semantan for ceiling structures; madu for floor joists and roof beams; lemang for roof joists; and secondary flooring bamboo elements conservatively estimated using equivalent structural values. As presented in Table 4, the total estimated biogenic carbon stored in the bamboo hall was 48,695 kg C, equivalent to 178,548 kg CO₂e. These findings demonstrate the substantial carbon storage potential of bamboo construction and provide the quantitative basis for subsequent lifecycle carbon comparison against embodied and operational emissions.

Table 4: Estimated biogenic carbon storage potential by structural component in the bamboo hall

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No.	Structural Component	Bamboo Type / Equivalent Material Category	Number of Bamboo Culms*	Estimated Carbon Storage per Culm (kg C)	Total Estimated Carbon Storage (kg C)
1	Columns	<i>Dendrocalamus asper</i> (Betung)	18	142.6	2,566.4
2	Flooring	<i>Dendrocalamus asper</i> (Betung) – floor beams	14	142.6	1,996.4
		<i>Gigantochloa albociliata</i> (Madu) – floor joists	42	276.5	11,611.7
		Secondary flooring bamboo elements**	64	68.6	4,390.4
3	Ceiling	<i>Gigantochloa scortechinii</i> (Semantan)	60	268.2	16,092.0
4	Roof	<i>Dendrocalamus asper</i> (Betung) – roof trusses	10	142.6	1,426.0
		<i>Gigantochloa albociliata</i> (Madu) – roof beams	24	276.5	6,636.0
		<i>Schizostachyum brachycladum</i> (Lemang) – roof joists	58	68.6	3,978.8
	Total Estimated Biogenic Carbon Storage				~48,695 kgC
					178,548 kg CO ₂ e

* Estimation based on an average bamboo culm length of 14 feet used in the construction inventory.

** Carbon storage for secondary flooring bamboo elements was conservatively estimated using the equivalent structural carbon value of *Schizostachyum brachycladum* due to unavailable direct specific species photosynthetic measurements.

Phase 2: Embodied Carbon Emission

Phase 2 quantified embodied carbon emissions associated with bamboo harvesting, processing, transportation, and on-site installation activities within the defined lifecycle boundary. The total embodied carbon emission for the bamboo hall was estimated at 442 kg CO₂e, representing the cumulative impact of material preparation and construction-related activities prior to building operation.

As shown in Table 5, transportation contributed the highest share of embodied emissions (56.8%), accounting for most of total embodied carbon due to repeated logistics between bamboo sourcing locations, processing sites, and the construction site. This indicates that transportation distance and vehicle fuel consumption are key determinants of embodied carbon performance in bamboo construction projects. Installation activities contributed the second largest proportion (41.2%), primarily due to electricity consumption from assembly equipment such as hand drills, air compressors, and grinders. In contrast, harvesting and processing activities contributed comparatively minor emissions (2.0%).

Despite the inclusion of multiple lifecycle activities, the embodied carbon burden remained relatively low when compared with the total estimated biogenic carbon stored in the bamboo structure (178,548 kg CO₂e). This suggests that bamboo construction can maintain a favourable embodied carbon profile when locally sourced materials and relatively low energy processing methods are adopted.

Table 5: Embodied carbon emissions from bamboo hall construction activities

Lifecycle Stage	Equipment / Activity Included	Carbon Emissions (kg CO ₂ e)	Contribution (%)
Harvesting & Processing	Pole saw, chain saw, grass cutter, grinder, generator, bamboo splitting machine, water pressure gun, hand drill	8.9	2.0
Transportation	Material transport between bamboo source, workshop, and construction site	251.0	56.8
Installation	Hand drill, air compressor, grinder	182.2	41.2
Total Embodied Carbon		442.1	100.0

Phase 3: Operational Carbon Emissions

Phase 3 assessed the projected operational carbon emissions associated with electricity consumption during the use phase of the bamboo hall over the assumed 30-year service life. Operational energy demand was estimated based on projected use of plug points, ceiling fans, and LED lighting under defined daily operating assumptions, with carbon emissions calculated using Malaysia's 2025 electricity grid emission factor.

As presented in Table 6, the total estimated annual operational carbon emission was 625.5 kg CO₂e, equivalent to 18,765 kg CO₂e over the 30-year building lifespan. LED lighting contributed the largest proportion of annual operational emissions (286.8 kg CO₂e/year), followed by ceiling fan operation (239.1 kg CO₂e/year) and plug-point electricity use (99.6 kg CO₂e/year). These findings indicate that extended operational hours and cumulative electricity demand significantly influence lifecycle carbon performance, even in low-carbon construction systems.

Compared with embodied carbon emissions (442.1 kg CO₂e), operational emissions were substantially higher over the building lifespan, highlighting the importance of operational energy efficiency in long-term carbon management. Nevertheless, when compared against the estimated biogenic carbon storage of the bamboo hall (178,548 kg CO₂e), projected operational emissions remained comparatively low under the defined assumptions. This suggests that bamboo-based construction, when combined with energy-efficient operation, may serve as a nature-based solution (NbS) for climate change mitigation through reduced lifecycle emissions and long-term biogenic carbon storage.

Table 6: Projected operational carbon emissions from bamboo hall electricity use

Electrical Usage	Number of Units	Power Rating (kW)	Daily Operating Hours	Daily Energy Consumption (kWh)	Grid Emission Factor (kg CO ₂ e/kWh)	Annual Carbon Emissions (kg CO ₂ e/year)
Plug Points	2	0.05	4	0.40	0.682	99.6
Ceiling Fan	1	0.12	8	0.96	0.682	239.1
LED Lighting	4	0.024	12	1.15	0.682	286.8
Total Annual Operational Carbon						625.5
Projected 30 Years Operational Carbon						18,765

Net Carbon Balance and Integrated Lifecycle Comparison

The overall net carbon performance of the bamboo hall was determined by comparing total biogenic carbon storage against combined embodied and operational lifecycle emissions within the defined assessment boundary. As summarised in Table 7, the bamboo hall demonstrated an estimated biogenic carbon storage of 178,548 kg CO₂e, while total embodied carbon emissions amounted to 442.1 kg CO₂e, and projected operational carbon emissions over the 30 years service life totalled 18,765 kg CO₂e.

Table 7: Integrated lifecycle carbon balance of the bamboo hall

Carbon Component	Carbon Value (kg CO ₂ e)	Contribution to Total Lifecycle Emissions (%)
Biogenic Carbon Storage	178,548.0	—
Embodied Carbon Emissions	442.1	2.3
Operational Carbon Emissions (30 years)	18,765.0	97.7
Total Lifecycle Emissions	19,207.1	100.0
Net Carbon Balance	-159,340.9	—

The combined lifecycle emissions were therefore estimated at 19,207.1 kg CO₂e, substantially lower than the total biogenic carbon stored in the bamboo structure. This resulted in a net carbon balance of -159,340.9 kg CO₂e, indicating that, under the defined system boundary and operational assumptions, the bamboo hall functioned as a net carbon sink rather than a net carbon source.

Operational carbon emissions represented the largest proportion of lifecycle emissions (97.7%), while embodied carbon emissions contributed only 2.3%. These findings suggest that although bamboo construction demonstrates strong carbon storage potential, long-term operational energy use remains the dominant emission driver within the lifecycle assessment boundary.

However, this carbon-negative outcome is conditional upon the assumptions adopted in the present study, including the exclusion of foundation construction, maintenance and replacement activities, demolition processes, and end-of-life carbon release scenarios. Changes in service life, electricity grid emission factors, operational usage intensity, or material transport distances may alter the final carbon balance. Nevertheless, under the defined lifecycle boundary, the bamboo hall demonstrated a favourable net carbon performance.

Carbon Performance Interpretation

The findings demonstrate that bamboo construction can achieve a favourable lifecycle carbon profile when biogenic carbon storage is considered alongside embodied and operational emissions within a defined assessment boundary. The estimated biogenic carbon storage of the bamboo hall (178,548 kg CO₂e) substantially exceeded total lifecycle emissions (19,207.1 kg CO₂e), resulting in a net carbon balance of -159,340.9 kg CO₂e. This indicates that, under the assumptions adopted in this study, the bamboo hall functioned as a net carbon sink over its assessed lifecycle.

The results further reveal that operational carbon emissions constituted the dominant emission source (97.7% of total lifecycle emissions), while embodied carbon emissions contributed only a minor share (2.3%). This differs from conventional building carbon assessments, where embodied emissions from cement, steel, and manufactured materials frequently dominate early lifecycle stages. In the present case, the relatively low embodied carbon burden reflects the

use of lightweight bamboo materials, low-energy processing activities, and simplified construction methods.

From a climate mitigation perspective, bamboo-based construction may also be interpreted as a potential nature-based solution (NbS), as it combines renewable biological material utilisation with measurable carbon storage in long-lived structural applications. Unlike conventional carbon intensive construction materials, bamboo enables atmospheric carbon captured during biological growth to remain stored within the built environment over the service life of the structure.

Comparison with Previous Studies

The present findings are broadly consistent with previous studies reporting the carbon mitigation potential of bamboo as a construction material. Xu et al. (2022) similarly highlighted the importance of integrating carbon sequestration and lifecycle emissions when evaluating bamboo construction performance, emphasising that biogenic carbon storage can substantially improve the environmental profile of plant-based building materials when assessed over an appropriate lifecycle boundary.

However, differences in reported carbon outcomes across studies are strongly influenced by methodological assumptions, including system boundary definition, service life assumptions, operational energy scenarios, transport distances, and treatment of end-of-life carbon release. In the present study, operational emissions emerged as the dominant lifecycle emission source, whereas studies involving more energy-intensive material processing or extended transportation logistics may report higher embodied carbon contributions. This highlights the sensitivity of lifecycle carbon outcomes to project-specific assumptions and reinforces the need for transparent boundary definition in comparative carbon accounting.

Planning Implications and Study Limitations

The findings provide several implications for planning and low-carbon built environment strategies, particularly in tropical regions where bamboo is naturally abundant and can be integrated into regional construction supply chains. Since transportation was identified as the dominant embodied carbon contributor, reducing procurement distance through decentralised processing facilities and regional material sourcing could further improve the lifecycle carbon performance of bamboo construction. Similarly, because operational emissions represented the largest proportion of lifecycle emissions, integrating passive cooling strategies, energy-efficient lighting systems, and reduced operational energy demand would strengthen long-term carbon outcomes in bamboo-based developments.

Bamboo offers advantages over timber due to shorter maturation cycles, regenerative harvesting through rhizome retention, and increasing applicability in engineered structural systems (Dai, 2026). From a structural perspective, recent advances in engineered bamboo products, preservation treatment, and construction detailing have significantly improved the durability, dimensional stability, and long-term applicability of bamboo in permanent building systems (Dai, 2026). These innovations increase the feasibility of substituting more carbon-intensive materials such as reinforced concrete, steel, aluminium, and glass in selected structural or semi-structural applications, particularly in tropical development contexts where bamboo resources are locally available.

From a climate mitigation perspective, bamboo construction may also be interpreted as a potential nature-based solution (NbS), as it extends biological carbon sequestration into the built environment through renewable structural materials. This aligns with planning strategies that seek to integrate ecological processes, low-carbon material transitions, and climate-responsive development pathways into future urban and landscape development practice.

However, the carbon-negative outcome reported in this study should be interpreted within the defined assessment boundary and methodological assumptions. Several lifecycle stages were excluded, including foundation construction, maintenance and replacement activities, demolition processes, waste treatment, and end-of-life carbon release. The operational assessment was based on projected electricity usage assumptions over a 30-year service life using Malaysia's 2025 electricity grid emission factor, which may vary over time. In addition, secondary flooring bamboo elements were conservatively estimated using equivalent structural carbon values due to unavailable direct species-specific measurements.

These methodological considerations indicate that the reported net carbon balance represents a case-specific estimate under the defined lifecycle boundary rather than a universally generalisable benchmark. Nevertheless, the findings demonstrate the strong carbon mitigation potential of bamboo construction when lifecycle boundaries, operational assumptions, and material sourcing strategies are appropriately managed.

CONCLUSIONS

This study demonstrates the strong potential of bamboo construction as a low-carbon building strategy within tropical built environment contexts when assessed using a lifecycle carbon framework integrating carbon sequestration, embodied emissions, and operational emissions. Under the defined assessment assumptions, the bamboo hall functioned as a net carbon sink, indicating that biogenic carbon storage substantially exceeded total lifecycle emissions. These findings support bamboo's potential role as a nature-based solution (NbS) for

climate change mitigation, particularly in regions where bamboo is locally available as a rapidly renewable material. From a planning perspective, the study highlights the importance of local material sourcing, transportation efficiency, and operational energy management in improving lifecycle carbon performance. Although the reported carbon-negative outcome remains conditional upon the defined system boundary and excluded lifecycle stages, this study provides practical evidence supporting the integration of bamboo-based construction into climate-responsive and sustainable development strategies.

ETHICS STATEMENT

Formal ethical approval was not required, as expert consultation was limited to technical verification of construction inventory data.

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