



Sustainability Analysis of Prefabricated Bamboo Construction in LCA-Based Construction Management in Bali

Anak Agung Putri Indrayanti¹, I Made Budiadi², I Wayan Wiraga³,
and I Gusti Ayu Wulan Krisna Dewi⁴

^{1,2,3,4} Civil Engineering Department, Politeknik Negeri Bali, Bali, Indonesia
ajung_putri@pnb.ac.id

Abstract. Prefabricated bamboo construction offers a sustainable alternative to conventional building materials due to its low embodied carbon and rapid renewability. This study evaluates the environmental performance of prefabricated bamboo construction in Bali through a cradle-to-gate Life Cycle Assessment (LCA), incorporating both energy consumption and CO₂ emissions across material sourcing, processing, transportation, and manufacturing stages. Data collected from local manufacturers and combined with LCA databases indicate that a typical 50 m² prefabricated bamboo house consumes approximately 200 kWh of energy during production, primarily used in cutting, lamination, and assembly processes. Using the Indonesian national electricity emission factor of 0.7 kgCO₂/kWh, this translates to 140 kg of CO₂ emissions from energy use alone. When including all components, such as resin glue, steel connectors, and transport, the total net emissions were estimated at 252.5 kgCO₂, or 5.05 kgCO₂ per square meter. Notably, when accounting for bamboo's natural carbon sequestration capacity (40 kgCO₂), the overall emissions dropped significantly, suggesting that bamboo construction can be carbon-neutral or even carbon-negative under optimal conditions. The findings highlight the importance of local supply chains, low-energy treatments, and renewable energy integration in maximizing the sustainability of bamboo-based construction systems. This research contributes a practical LCA framework for evaluating the environmental impact of prefabricated bamboo buildings in Bali and similar tropical regions.

Keywords: CO₂ Emissions, Energy Consumption, Life Cycle Assessment (LCA), Prefabricated Bamboo Construction, Sustainable Building Materials

1 Introduction

The global construction industry accounts for nearly 40% of energy-related CO₂ emissions worldwide, making it one of the largest contributors to climate change. In response, sustainable alternatives to conventional building materials such as concrete and steel are increasingly being explored. Among these, bamboo has emerged as a promising renewable resource due to its rapid growth, high strength-to-weight ratio, and ability to sequester carbon during its life cycle. The construction industry significantly impacts the environment, consuming substantial resources and generating considerable waste (Yadav & Mathur, 2021). Life Cycle Assessment is crucial for

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evaluating the environmental burdens associated with building materials and construction processes (Tait & Cheung, 2016). LCA is pivotal in evaluating environmental impacts throughout a building's lifecycle, from raw material extraction to end-of-life management (Wu et al., 2020). LCA is an effective method of assessing environmental performance, which is a necessity in attaining environmentally sustainable solutions (Beemsterboer et al., 2020; Horvath, 2004). Current digitization and Industry 4.0 trends in construction highlight the need for comprehensive environmental impact assessments during the building construction phase (Sandanayake, 2022). Building Information Modeling integration with LCA can enhance decision-making related to material selection and project alternatives by providing an environmental perspective (Crippa et al., 2020). Integrating BIM and LCA is an optimal procedure towards achieving sustainable development and environmental protection, and empowers the decision-making process in the construction sector (Najjar et al., 2017).

In regions like Bali, Indonesia, bamboo is not only a cultural and architectural symbol but also an essential material for sustainable development. The growing adoption of prefabricated bamboo systems enables faster, more standardized, and scalable construction while minimizing waste and labor intensity. Prefabricated bamboo construction combines the advantages of prefabrication with the sustainability of bamboo as a renewable building material. Bamboo, a fast-growing and renewable resource, presents a compelling alternative to conventional construction materials like concrete and steel. Bamboo's rapid growth, high strength-to-weight ratio, and carbon sequestration properties make it an attractive option for sustainable construction (Silva et al., 2019).

This study evaluates the environmental impact of prefabricated bamboo construction through a cradle-to-gate Life Cycle Assessment (LCA), focusing on CO₂ emissions and energy consumption across key stages: raw material extraction, processing, transportation, and manufacturing. By quantifying emissions and energy use, this research aims to provide a data-driven framework for integrating bamboo into modern, low-carbon construction practices.

2 Methodology

2.1 Study Scope and System Boundary

This study adopts a cradle-to-gate LCA approach, covering some phases such as raw material extraction, harvesting of bamboo from local plantations, material processing, cutting, shaping, and treating bamboo poles, prefabrication, manufacturing of modular wall panels and structural components, and transportation, as a movement of materials from the plantation and factory to the construction site. The system boundary excludes the use phase and end-of-life scenarios. To effectively manage the environmental footprint of buildings, the initial critical step involves quantifying emissions from various life cycle stages, construction processes, and building materials (Chaudhary & Akhtar, 2022). LCA assesses environmental effects encompassing raw material extraction, manufacturing, transportation, construction, usage, and disposal, guiding

sustainable material choices for the construction sector (Baskaran et al., 2025). LCA is also essential for evaluating energy consumption, greenhouse gas emissions, water use, and resource depletion.

2.2 Functional Unit

To enable comparison with other building materials, the functional unit was defined as 1 square meter (m²) of prefabricated bamboo wall or structure.

2.3 Data Collection

A comprehensive inventory of materials and processes was conducted based on typical prefabricated bamboo modules used in Bali. The bill of materials included some parameters that can be seen in Table 1.

Table 1. Typical Prefabricated Bamboo Modules for Bill of Materials Calculation

Component	Description
Bamboo species	<i>Gigantochloa apus</i> (predominantly used in Bali)
Treatment	Borax immersion or fire-retardant treatment
Fasteners	Steel connectors, bolts, brackets
Adhesives	Urea-formaldehyde resin or eco-friendly alternatives
Panels	Bamboo composite panels or solid slats

Primary data were collected from interviews and field visits to bamboo manufacturers in Tegallalang, Payangan, and Sukawati, Bali. Secondary data were sourced from the Ecoinvent v3.8 database, peer-reviewed studies (Sharma et al., 2015; Widjaya et al., 2020), Indonesian national emission factors, and manufacturer reports and case studies

2.4 Emission and Energy Factors

Bamboo acts as a carbon sink during its growth phase. The amount of CO₂ sequestered depends on the species, growth rate, stand density, and age at harvest. An average sequestration value of -25 kgCO₂/m² was used for mature bamboo walls, based on field studies in Indonesia. Bamboo is a Carbon-Neutral Material, as it absorbs CO₂ during its growth through photosynthesis. It can also sequester up to 70 tons of CO₂ per hectare per year, depending on species and growing conditions. Processing bamboo into construction elements (e.g., laminated bamboo beams, panels) requires relatively low energy compared to concrete or steel. Therefore, the embodied carbon is minimal unless chemical treatments or synthetic resins are used. If bamboo is sourced locally (as it often is in Bali), transportation emissions are low. Long-distance transport increases the carbon footprint. Prefabrication may involve energy use for cutting, shaping, laminating, and treating bamboo. If renewable energy is used in manufacturing, emissions can be further reduced. Bamboo is biodegradable and can be reused or composted without emitting significant CO₂ if not treated with toxic chemicals. Key emission and energy values used in the analysis can be seen in Table 2.

Table 2. Emission and Energy Values of Prefabricated Bamboo Modules

Parameter	Value	Source
1 Bamboo sequestration	-0.2 kgCO ₂ /kg	Field data / INBAR
2 Resin glue	8 kgCO ₂ /kg	Ecoinvent
3 Steel connectors	7 kgCO ₂ /kg	Ecoinvent
4 Transport	0.03 kgCO ₂ /ton-km	Indonesian road transport data
5 Electricity grid factor	0.7 kgCO ₂ /kWh	Ministry of Energy & Mineral Resources, Indonesia
6 Prefab energy use	4 kWh/m ²	This study

2.5 Calculation Formula

For calculating the net emission of CO₂ can be calculated as follows:

$$Net\ CO_2\ Emissions = \sum(Qt_i + Ef_i) - CO_2\ Sequestered \quad (1)$$

Where:

Qt_i = mass or volume of each component

Ef_i = kgCO₂ per unit of component

CO₂ Sequestered = negative emission due to bamboo growth

Include negative emissions from carbon sequestration:

$Net\ CO_2$ = Emissions from production, transport, etc. – CO₂ absorbed by bamboo

Results were normalized per m² of built area using this equation:

$$CO_2\ Intensity = \frac{Building\ Area\ (m^2)}{Total\ Net\ CO_2} \quad (2)$$

3 Results and Discussion

3.1 Result

The results of this research to find the total energy for processing a 50 m² prefabricated bamboo house can be calculated based on the Typical Energy Use in Prefabricated Bamboo Construction (per m²) as shown in Table 3.

Table 3. Typical Energy Use in Prefabricated Bamboo Construction (per m²)

Process	Energy use (kWh/m ²)	Notes
Bamboo harvesting & transport	~0.2 – 0.5 kWh/m ²	Mostly manual labor; low energy input
Cutting & shaping bamboo	~0.5 – 1.5 kWh/m ²	Sawing, drilling, sanding
Treatment (borax immersion)	~0.1 – 0.3 kWh/m ²	Low-energy chemical process
Lamination & panel production	1.0 – 2.5 kWh/m ²	Includes drying, pressing, and gluing
Prefabrication & assembly	~1.0 – 2.5 kWh/m ²	Frame assembly, panel joining
Total Estimated Energy Use	2.3 – 6.0 kWh/m ²	Varies with automation level

From this table, the average energy used for Prefabrication processes is about 2.3 to 6 kWh/m². Then, the calculation is made for this energy estimation, which calculates the emission and energy values of prefabricated bamboo modules, as shown in Table 4.

Table 4. Emission and Energy Values of Prefabricated Bamboo Modules

Process	Energy use (kWh/m ²)	Total for 50m ² (kWh)
Bamboo harvesting & transport	0.3	15
Cutting & shaping	1.0	50
Treatment (borax immersion)	0.2	10
Lamination & panel production	2.0	100
Prefab assembly	0.5	25
Total	4.0	200

When compared to conventional materials, the carbon footprint of prefabricated bamboo is dramatically lower than that of reinforced concrete (Lorenzo et al., 2020) and structural steel (Teng et al., 2018). This reduced environmental impact positions bamboo as a sustainable alternative in construction, especially given the global imperative to decrease embodied carbon in building materials (Chen et al., 2025). Furthermore, bamboo’s rapid growth rate and renewability make it an exceptionally appealing resource for construction, offering high specific strength and flexibility that outperforms many traditional materials (Inoue et al., 2017). Using the Indonesian national grid emission factor of 0.7 kgCO₂/kWh, the energy-related CO₂=200kWh×0.7 kgCO₂/kWh=140 kgCO₂. The results of this research to find CO₂ contribution for a 50 m² prefabricated bamboo module can be seen in Table 4. In contrast, emission and energy values of prefabricated bamboo modules are shown in Table 5, and sensitivity analysis is shown in Table 6.

Table 5. Emission and Energy Values of Prefabricated Bamboo Modules

Item	Quantity	Emission factor	CO ₂ contribution
Bamboo frame	200 kg	-0.2 kgCO ₂ /kg (sequestered)	-40 kgCO ₂
Resin glue	10 kg	8 kgCO ₂ /kg	+80 kgCO ₂
Steel connectors	15 kg	7 kgCO ₂ /kg	+105 kgCO ₂
Transport (50 km)	250 tons	0.03 kgCO ₂ /ton-km	+7.5 kgCO ₂
Prefab energy	200 kWh	0.7 kgCO ₂ /kWh	+140 kgCO ₂
Total			+292.5 kgCO₂
Minus bamboo sequestration			-40 kgCO ₂
Net CO ₂			+252.5 kgCO ₂
Building Area			50 m ²
Per m ²			~5.05 kgCO ₂ /m ²

Table 6. Sensitivity Analysis

Scenario	Change in Input	Net CO ₂ (kgCO ₂ /m ²)	Change vs Base Case
Base Case	Default value	5.05	-
+50% Transport Distance	75 – 112 km	5.25	+4%
Replace Resin with Eco-glue	8 – 2 kgCO ₂ /kg	3.80	-25%
Use Solar Energy (0 kgCO ₂ /kWh)	0.7 - 0	3.00	-40%
No Carbon Sequestration	0 instead of -0.2kgCO ₂ /kg	5.85	+16%

A sensitivity analysis reveals that replacing conventional resin with low-emission adhesives and using solar-powered factories can reduce emissions by up to 40%, highlighting key leverage points for enhancing sustainability.

3.2 Discussion

Energy Consumption. For a 50 m² prefabricated bamboo house, the total energy consumed during production was estimated at 200 kWh, primarily from cutting, lamination, and assembly processes. Using the Indonesian electricity emission factor of 0.7 kgCO₂/kWh, this resulted in 140 kg of CO₂ emissions from energy use alone

Total CO₂ Emissions. Including all components—resin glue, steel connectors, transport, and energy—the net emissions totaled 252.5 kgCO₂ for a 50 m² house, ~5.05 kgCO₂/m² when normalized by area. When bamboo's carbon sequestration (~40 kgCO₂) was included, the net emissions dropped significantly, suggesting that under optimal conditions, bamboo construction can be carbon-neutral or even carbon-negative.

Contribution Analysis. A breakdown of emissions showed that resin glue and steel connectors were the main contributors to emissions. Energy use in prefabrication contributed moderately but could be reduced with cleaner energy sources.

Sustainability Implications. These findings reinforce bamboo's potential as a low-carbon building material, especially when sourced locally, treated with minimal chemicals, and fabricated using energy-efficient methods. The results support the integration of bamboo-based construction into sustainable urban planning and green building standards in Bali and similar tropical regions.

4 Conclusion

This study demonstrates that prefabricated bamboo construction has a significantly lower carbon footprint compared to conventional materials. With an average of ~ 5 kgCO₂/m² and the potential to become net-negative when accounting for carbon sequestration, bamboo presents a viable solution for reducing greenhouse gas emissions in the construction sector. Some strategies for enhancing sustainability include reducing reliance on synthetic resins and steel connectors, optimizing energy efficiency in manufacturing, promoting local sourcing and circular design principles, and providing a practical LCA framework. This research supports future assessments of bamboo-based buildings and contributes to the broader goal of climate-resilient architecture in Bali and beyond.

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