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Digital vernacular approach for low-carbon tropical social housing: A comparative study using engineered bamboo and parametric design

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Abstract

The building sector is responsible for approximately 37 percent of global energy-related carbon emissions, with embodied carbon becoming increasingly critical in sustainable construction. This study presents a digital vernacular framework that integrates bio-based materials, parametric design, and passive climatic strategies for low-carbon tropical social housing. A comparative analysis was performed using a 54 sqm housing prototype in coastal Ecuador, evaluating two structural systems: reinforced concrete and a digitally calibrated bamboo-based structure. The methodology combines life cycle assessment (LCA), parametric structural optimization, passive thermal evaluation, and cost analysis. The results indicate that the bamboo-based system reduced embodied carbon emissions by approximately 65 percent compared with reinforced concrete construction. In addition, parametric structural calibration improved material efficiency by 12–18 percent. Passive thermal performance analysis demonstrated a reduction in indoor temperatures of 3–5°C, enhancing thermal comfort in humid tropical climates. These findings confirm that integrating digital design tools with renewable structural materials significantly improves environmental and socio-economic performance. The proposed digital vernacular framework offers a scalable approach to climate-resilient, low-carbon housing in rapidly urbanizing regions. Unlike previous studies that separately investigate bio-based materials, passive design, or parametric optimization, the present study integrates these components into a unified comparative framework for tropical social housing. However, the findings should be interpreted as a comparative exploratory assessment rather than a fully validated predictive model, due to simplified thermal modeling assumptions and the exclusion of operational and end-of-life stages from the LCA. The study also highlights the relevance of recent Chinese advancements in engineered bamboo technologies as a reference framework for cross-regional sustainable housing strategies in tropical regions. Furthermore, the study is contextualized within recent Chinese advancements in engineered bamboo construction, highlighting opportunities for cross-regional knowledge transfer and South–South collaboration in sustainable architecture.

Keywords: Digital vernacular; Engineered bamboo; Parametric design; Low-carbon housing; Life cycle assessment; Tropical architecture; Sustainable construction; Bio-based materials

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1. Introduction

The building sector accounts for nearly 37 percent of global energy-related carbon emissions, with embodied carbon in construction materials representing an increasingly significant share as operational energy efficiency improves. Recent global assessments have indicated that the building sector remains one of the largest contributors to greenhouse gas emissions worldwide (United Nations Environment Programme [UNEP], 2022). According to the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (IPCC, 2023), rapid decarbonization of cement and steel production is essential to achieving mid-century climate targets. Life cycle assessment (LCA) studies have indicated that structural systems constitute a major proportion of total embodied emissions in residential buildings, particularly in reinforced concrete-based typologies (Cabeza *et al.*, 2021; Chastas *et al.*, 2016; Dixit, 2017; Dodoo *et al.*, 2014).

These challenges are particularly evident in the Global South, where rapid urbanization coincides with climate vulnerability and housing shortages. Latin America and tropical regions of China face comparable pressures associated with demographic growth, urban expansion, and the need for affordable housing adapted to humid and warm climates. In Latin America, these pressures intersect with structural housing deficits and increasing exposure to climate-related risks such as flooding, heat stress, and coastal erosion (Economic Commission for Latin America and the Caribbean [ECLAC], 2023). Coastal Ecuador exemplifies this convergence, where high humidity, elevated temperatures, and informal settlement growth require construction strategies that combine climatic responsiveness with economic accessibility.

Similarly, tropical regions of southern China, including provinces such as Yunnan, Guangxi, and Hainan, face comparable climatic conditions and have become important laboratories for experimentation in bio-based construction and rural revitalization strategies. In recent years, Chinese research institutions and industry have developed advanced engineered bamboo materials such as Glubam and Scrimber, transforming bamboo from a vernacular building material into an industrial structural resource (Sharma *et al.*, 2015). These developments form part of broader initiatives, such as the "Bamboo as a Substitute for Steel and Plastic" program, which aim to reduce reliance on carbon-intensive materials while promoting renewable biological resources.

Despite these advances in bio-based construction materials and digital design methodologies, most previous studies have investigated either the environmental performance of bamboo materials, passive climatic strategies, or computational structural optimization independently. However, limited research has critically examined how these components can operate simultaneously within a unified design methodology for tropical social housing.

Furthermore, existing literature rarely addresses how computational design frameworks may facilitate the integration of vernacular construction traditions with industrialized engineered bamboo systems across different regional contexts. This gap is particularly evident in comparative studies involving Latin America and China. There remains a lack of integrated studies that simultaneously address structural optimization, embodied carbon reduction, and passive climatic performance within a unified design framework. In particular, limited research has explored how digital design tools can bridge vernacular construction practices and engineered bio-based materials across different regional contexts, including comparative perspectives between Latin America and China.

Recent studies have demonstrated that bamboo possesses a high strength-to-weight ratio, favorable mechanical performance, and a significantly lower environmental impact compared with reinforced concrete systems (Correal *et al.*, 2014; Sharma *et al.*, 2015; Vogtländer *et al.*, 2010). Nevertheless, the variability of biological materials and the absence of standardized structural verification procedures often hinder their broader adoption in formal housing construction. In this context, advances in digital design and parametric modeling offer new opportunities for integrating natural material variability into structural evaluation and optimization processes.

Parametric modeling environments enable designers to incorporate real geometric variability of biological materials into computational structural analysis. Rather than treating irregularity as a limitation, digital workflows can integrate measured geometry directly into performance-based design processes, reducing excessive material safety factors and improving eco-efficiency (Chastas *et al.*, 2016; Dixit, 2017). These tools allow biological materials such as bamboo to be evaluated according to contemporary engineering standards while preserving their ecological advantages.

The concept of digital vernacular provides a framework for integrating traditional material knowledge with advanced computational design methods. Rather than romanticizing vernacular architecture as a purely historical phenomenon, this approach interprets vernacular construction intelligence through digital mediation. In this model, computational design tools enable natural materials and local construction traditions to meet contemporary structural, environmental, and regulatory requirements.

This study proposes a digital vernacular framework that combines parametric structural calibration, bio-based material systems, circular-economy principles, and passive climatic strategies within a unified design methodology. Through a comparative case study of social housing in coastal Ecuador, the research evaluates the potential of digitally optimized bamboo structures to reduce embodied carbon while maintaining structural performance and improving thermal comfort.

By situating this Latin American case study within the broader context of Chinese innovations in engineered bamboo construction, the research highlights a potential South–South exchange of architectural knowledge. Chinese advances in bio-based industrial materials provide technological insights, while Latin American vernacular bamboo construction offers long-standing climatic adaptation strategies. Together, these perspectives suggest new pathways to climate-resilient and low-carbon social housing in tropical regions.

Accordingly, this study addresses the following research questions:

(i) How does a digitally calibrated bamboo structural system compare with reinforced concrete in terms of embodied carbon and thermal performance?
(ii) To what extent can parametric structural optimization improve the eco-efficiency of bio-based housing systems?
(iii) How can the digital vernacular framework support the integration of vernacular construction practices with contemporary engineering requirements?

The main contribution of this study is the development of an integrated digital vernacular framework that combines parametric structural calibration, bio-based material systems, and passive climatic design within a unified methodological approach. The research not only quantifies environmental, thermal, and economic performance improvements but also demonstrates how computational design can bridge vernacular construction practices and contemporary engineering standards. By incorporating a comparative perspective that includes Chinese advancements in engineered bamboo construction, the study contributes to the emerging discourse on cross-regional knowledge transfer and sustainable architectural development in the Global South.

2. Literature review

Vernacular architecture has historically evolved in response to climatic conditions, material availability, and local construction knowledge. In many regions of Latin America, traditional building systems such as adobe, rammed earth, bahareque, and bamboo structures developed through long-term adaptation to environmental conditions. This relationship between culture, climate, and construction practices has been extensively documented in vernacular architecture studies (Oliver, 2006). Vernacular housing forms are strongly influenced by environmental and socio-cultural factors (Kirchherr *et al.*, 2018; Rapoport, 1969). These systems typically demonstrate favorable thermal performance, vapor permeability, and low embodied energy compared with industrial construction materials. From a life-cycle perspective, vernacular materials are inherently aligned with contemporary sustainability objectives due to their reliance on locally available resources and low-energy production processes (Cabeza *et al.*, 2021; Chastas *et al.*, 2016).

However, throughout the 20th century, modernization processes reshaped material hierarchies in architecture and construction. Reinforced concrete gradually became institutionalized as the dominant structural system across much of Latin America. National housing programs, urban planning policies, and construction regulations increasingly favored industrial materials associated with durability, standardization, and technological progress. As a result, vernacular materials were frequently marginalized or perceived as temporary and technically inferior solutions. This transformation was not only technical but also economic and political, embedding building production within globalized supply chains dominated by cement and steel industries.

Despite these structural changes, a significant portion of housing in Latin American cities continues to be produced through incremental and self-built processes. Such informal construction practices demonstrate considerable social resilience and adaptability but often rely on reinforced concrete and masonry, as these materials are recognized within regulatory frameworks and widely available through established markets. Consequently, bamboo—despite its mechanical potential and environmental advantages—remains only partially integrated into formal housing systems.

In contrast, developments in China illustrate a different trajectory in the modernization of bio-based construction materials. Over the past 2 decades, Chinese research institutions and construction industries have invested significantly in engineered bamboo products, including Glubam, laminated bamboo composites, and Scrimber technologies. These engineered bamboo systems differ significantly from untreated natural bamboo culms. Glubam consists of glued laminated bamboo strips assembled into structural members with standardized mechanical properties.

Laminated bamboo composites are produced through compression and adhesive bonding, which improve dimensional stability and structural consistency. Scrimber technology involves the compression of bamboo fiber bundles into dense structural panels or beams with enhanced strength and reduced material irregularity.

In contrast, natural bamboo construction typically relies on minimally processed culms that retain higher geometric variability and require additional structural adaptation during construction.

These innovations transform bamboo from a traditional vernacular resource into a standardized structural material capable of meeting modern engineering requirements. Experimental studies demonstrate that engineered bamboo systems can achieve high strength-to-weight ratios and structural performance comparable to conventional timber and steel components (Sharma *et al.*, 2015; Vogtländer *et al.*, 2010).

Chinese bamboo innovation is closely connected to broader policy initiatives, such as rural revitalization strategies and the "Bamboo as a Substitute for Steel and Plastic" program. These initiatives promote the industrial use of bamboo as a renewable alternative to carbon-intensive materials while simultaneously supporting regional economies and ecological resource management. Consequently, bamboo construction has been applied in bridges, public buildings, and experimental housing projects across several Chinese provinces, particularly in subtropical and tropical regions where bamboo resources are abundant.

While the Chinese experience demonstrates how bio-based materials can be successfully integrated into modern construction industries, bamboo architecture in Latin America remains largely associated with vernacular housing traditions. In countries such as Colombia and Ecuador, species such as *Guadua angustifolia* have long been used in housing construction due to their structural strength, availability, and adaptability to humid climates. Previous studies have confirmed that bamboo structures possess excellent mechanical properties and significantly lower embodied carbon compared with reinforced concrete systems (Correal *et al.*, 2014). Nevertheless, previous studies have also identified several unresolved barriers associated with bamboo construction. Durability concerns related to biological degradation, moisture exposure, and long-term maintenance remain significant challenges in humid climates.

In addition, regulatory acceptance of bamboo structures is still limited in many countries due to the absence of standardized verification procedures and building codes. Social perception also plays an important role, as bamboo is frequently associated with informal or temporary housing despite its demonstrated structural capacity.

These contradictions illustrate that the transition toward bio-based construction systems depends not only on material performance but also on institutional, cultural, and economic factors. Nevertheless, regulatory barriers, limited industrial processing infrastructure, and persistent perceptions regarding durability continue to constrain their broader adoption.

At the same time, advances in digital design technologies are transforming architectural methodologies. Parametric modeling and computational optimization enable designers to incorporate material variability directly into structural analysis. In bamboo construction, natural geometric variations, such as tapering, nodal irregularities, and wall thickness differences, have historically been treated as limitations. However, digital modeling environments allow these variations to be captured and integrated into performance-based structural calculations.

Rather than imposing industrial uniformity, computational design tools provide mechanisms for integrating biological variability into contemporary structural verification processes. This shift reframes irregularity not as uncertainty but as quantifiable material data. As a result, parametric modeling can reduce conservative safety factors traditionally applied to natural materials and improve structural eco-efficiency by minimizing unnecessary material consumption.

In parallel, the concept of the circular economy has emerged as a key framework for sustainable construction. Circular strategies emphasize local material sourcing, resource regeneration, and closed-loop production systems (Geissdoerfer *et al.*, 2017; Kirchherr *et al.*, 2018). In tropical regions, agricultural by-products such as rice husks, banana fibers, and sugarcane residues represent valuable biomass resources that can be integrated into insulation systems and bio-composite materials. The integration of bamboo structures with locally sourced agricultural materials therefore represents both a technological solution and a territorial strategy that strengthens regional economic cycles and reduces dependency on imported industrial materials.

Climatic adaptation is another critical dimension in tropical architecture. Housing in humid and warm climates must address overheating, high humidity, and limited access to mechanical cooling systems. Passive cooling strategies—including cross-ventilation, elevated roof structures, shading devices, and permeable building envelopes—have been widely documented as effective

approaches for improving indoor comfort (Santamouris, 2020). However, previous research often treats passive climatic design and embodied carbon reduction as separate issues, despite the strong interdependence between material selection and thermal performance.

The intersection of bio-based materials, digital design technologies, circular construction systems, and climatic adaptation remains insufficiently explored in the context of tropical social housing. In particular, limited studies have examined how engineered bio-material innovations developed in China can be integrated with vernacular bamboo construction traditions in Latin America through computational design frameworks.

To address this gap, the present study introduces the concept of digital vernacular as an integrative design framework that combines vernacular construction knowledge with digital structural calibration and bio-based material systems. Rather than viewing vernacular architecture as a static historical reference, this approach interprets traditional material intelligence through contemporary computational tools. In doing so, it enables natural materials to meet modern structural standards while preserving their ecological and climatic advantages.

By situating a tropical social housing prototype in coastal Ecuador within a comparative context that includes Chinese advancements in engineered bamboo construction, this research contributes to the broader discourse on South–South knowledge exchange in sustainable architecture. This perspective highlights the potential for combining technological innovation in bio-material engineering with long-standing vernacular construction practices to develop climate-responsive, low-carbon housing systems for rapidly urbanizing regions.

3. Materials and methods

This study employed an integrated performance-based methodology combining LCA, digital structural calibration, passive thermal evaluation, and comparative cost analysis. The proposed methodological framework enables the simultaneous assessment of environmental, structural, climatic, and economic performance within a unified analytical model.

A comparative prototype approach was adopted, in which two structural systems were evaluated under identical geometric, climatic, and functional conditions. This approach allows a direct comparison of material performance while minimizing the influence of external variables.

3.1. Case study selection and territorial context

A 54 sqm single-storey social housing prototype located in coastal Ecuador was selected as the case study. The prototype represents a typical model of incremental housing commonly developed in peri-urban settlements along the Ecuadorian coast.

The region is characterized by humid tropical climatic conditions, including mean annual temperatures between 24 °C and 28 °C, high relative humidity, seasonal flooding associated with El Niño events, and increasing heat stress due to climate change. These conditions provide an appropriate context for evaluating climate-responsive construction strategies.

The spatial geometry of the housing prototype was kept constant across all scenarios to ensure that performance differences arise solely from variations in structural systems and material configurations.

3.2. Comparative structural scenarios

Two structurally equivalent housing models were analyzed:

(i) Baseline scenario: Reinforced concrete frame with masonry infill, representing dominant formal construction practices.
(ii) Alternative scenario: Digitally calibrated bamboo structural system based on *G. angustifolia*, combined with bio-based insulation materials and lightweight envelope components.

The term "digitally calibrated bamboo structural system" refers to a bamboo construction methodology in which the natural geometric variability of *G. angustifolia* culms is digitally measured and integrated into computational structural models.

Unlike conventional bamboo construction approaches that rely on generalized dimensions, the proposed system incorporates measured geometric parameters, including culm diameter, wall thickness, tapering, and nodal distribution, into parametric structural optimization workflows. Both systems were designed to satisfy equivalent structural performance requirements under gravity loads and moderate seismic conditions typical of coastal Ecuador. Seismic performance was evaluated through comparative structural load analysis considering reduced structural mass, lateral stability, and simplified inertial response under moderate seismic loading conditions typical of coastal Ecuador.

Due to the exploratory scope of the study, a full nonlinear seismic simulation was not performed. Instead,

the assessment focused on comparative structural behavior between equivalent housing typologies. Structural equivalence was defined in terms of safety compliance and functional performance rather than identical geometric dimensions.

3.3. Digital structural calibration

To address the natural geometric variability of bamboo, representative culms were digitally documented using photogrammetry and laser scanning techniques. These methods enabled high-resolution capture of geometric parameters along the longitudinal axis. Measured parameters included:

- culm diameter variation
- wall thickness distribution
- nodal spacing
- tapering geometry

The collected data were incorporated into parametric structural models developed within the Rhino–Grasshopper computational environment. The modeling workflow enabled structural elements to be calibrated according to load combinations, slenderness ratios, and stability constraints.

Unlike conventional design approaches that rely on standardized dimensions, the digital calibration process integrates measured geometry directly into structural analysis. This approach reduces excessive material usage while maintaining structural safety margins. An iterative optimization routine was implemented to minimize material volume while preserving structural capacity, achieving a balance between load-bearing performance and carbon efficiency.

3.4. Life cycle assessment

The environmental assessment was conducted in accordance with International Organization for Standardization (ISO) 14040 and ISO 14044 standards. A cradle-to-construction system boundary (modules A1–A5) was adopted:

- A1–A3: Raw material extraction and production
- A4: Transportation
- A5: Construction and assembly

Operational energy use and end-of-life phases were excluded to isolate embodied carbon impacts. Emission factors were obtained from peer-reviewed LCA databases. Transportation distances were defined based on realistic supply chains:

- Bamboo and biomass materials: ≤100 km
- Cement and steel: national distribution networks

3.5. Eco-efficiency index

An eco-efficiency index (EEI) was introduced to evaluate the relationship between structural performance and environmental impact. The index relates load-bearing capacity to embodied carbon emissions. A simplified sensitivity analysis was additionally conducted to evaluate the influence of variations in bamboo density, transportation distance, and structural load assumptions on the EEI values.

The results demonstrated that although numerical values varied moderately, the comparative environmental advantage of the bamboo-based system remained consistent across all evaluated scenarios. This metric enables comparison between materially different systems while maintaining functional equivalence, allowing identification of configurations that achieve required safety levels with reduced carbon intensity.

3.6. Passive thermal assessment

Passive thermal performance was evaluated using simplified airflow and ventilation modeling adapted to humid tropical conditions. Airflow rates were estimated based on:

- building height differentials
- opening areas
- prevailing wind conditions
- cross-ventilation pathways

Indoor temperatures were estimated using simplified thermal balance assumptions incorporating ventilation rates, solar shading, and envelope permeability. Although simplified, the model provides reliable comparative insight into relative thermal comfort performance. The simplified thermal model was selected due to the exploratory and comparative nature of the study. Rather than predicting absolute indoor thermal conditions with high precision, the analysis aims to evaluate relative performance differences between structurally equivalent housing systems under identical climatic assumptions.

This approach is consistent with early-stage sustainable housing assessment methodologies frequently applied in comparative environmental design studies. Future research may expand this simplified thermal evaluation through full computational fluid dynamics (CFD) simulations capable of analyzing detailed airflow behavior, turbulence effects, humidity distribution, and localized thermal comfort conditions within bamboo-based housing systems. Such simulations would provide higher-resolution validation of passive ventilation performance under varying climatic and occupancy scenarios.

3.7. Cost assessment and supply chains

Construction costs were estimated using regional market data for materials, labor, transportation, and assembly processes. The bamboo system assumes localized harvesting and processing, while the reinforced concrete system relies on centralized industrial supply chains. This approach enables the evaluation of both direct construction costs and broader economic implications of material sourcing.

3.8. Methodological limitations

Several limitations should be acknowledged. The LCA scope excludes operational and end-of-life stages. Thermal analysis is based on simplified modeling rather than a full CFD simulation. In addition, extreme wind-loading conditions, such as hurricanes and cyclonic events, were not included in the structural assessment and therefore require further investigation in future studies. Structural calibration assumes consistent mechanical properties of bamboo samples. Despite these limitations, the integrated methodology provides a robust basis for comparative evaluation of low-carbon construction strategies in tropical environments.

4. Results

The comparative assessment of the 54 sqm prototype demonstrated clear and consistent advantages of the digitally calibrated bamboo-based system over the reinforced concrete baseline across environmental, structural, thermal, and economic performance indicators. The results confirm that sustainability improvements in tropical housing are achieved not through isolated material substitution, but through the integrated application of bio-based materials, digital structural calibration, and passive climatic design strategies.

4.1. Passive thermal performance

The thermal analysis revealed that the bamboo-based housing prototype achieved significantly improved passive ventilation performance compared with the reinforced concrete baseline. Simulated airflow rates in the bamboo structure ranged between 0.9 and 1.3 m^3/s, whereas the reinforced concrete scenario exhibited lower values of 0.3–0.5 m^3/s, primarily due to reduced envelope permeability and limited ventilation pathways.

Under peak daytime conditions with external temperatures reaching 32 °C, indoor temperatures in the reinforced concrete dwelling increased to 34–35 °C. In contrast, the bamboo structure maintained indoor temperatures within the range of 29–31 °C, corresponding to a reduction of 3–5 °C.

As a result, the bamboo-based system achieved 58–64 percent of occupied hours within the adaptive thermal comfort range, compared with 32–38 percent in the reinforced concrete model. These improvements are attributed to the combined effects of lightweight structural materials, permeable envelope systems, elevated roof geometry, and enhanced cross-ventilation pathways. However, the results should be interpreted cautiously because the thermal evaluation was based on simplified airflow assumptions rather than a full CFD simulation. Consequently, the reported temperature reductions represent comparative tendencies rather than exact predictive values.

The passive airflow performance of different structural systems was evaluated (Figure 1). Bamboo structures exhibited significantly higher airflow rates compared with concrete, confirming the effectiveness of permeable bio-based structural systems in enhancing natural ventilation.

4.2. Structural eco-efficiency

Although the reinforced concrete structure exhibited higher absolute compressive strength, the EEI analysis demonstrated superior performance of the bamboo-based system when structural capacity was evaluated in terms of embodied carbon. The results indicate that the bamboo structural system provides a more favorable balance between load-bearing capacity and environmental impact. This finding emphasizes the importance of evaluating structural systems based on performance-per-carbon efficiency rather than absolute strength alone.

Additionally, the reduced structural mass of bamboo construction may offer advantages in moderate seismic regions, such as coastal Ecuador, as lower mass reduces inertial forces during seismic events and may enhance structural resilience under dynamic loading conditions.

4.3. Embodied carbon performance

The embodied energy of the materials is presented in Figure 2. Concrete exhibited significantly higher embodied energy compared with bamboo.

The environmental impact in terms of CO_2 emissions is shown in Figure 3. Bamboo demonstrated substantially lower CO_2 emissions compared with reinforced concrete.

4.4. Economic feasibility

The cost analysis indicates that the bamboo structural system provides clear economic advantages relative to reinforced concrete construction. The reinforced concrete scenario required construction costs of 420–460 USD/sqm, while the bamboo-based system required 290–340 USD/sqm, corresponding to a cost reduction of 25–40 percent.

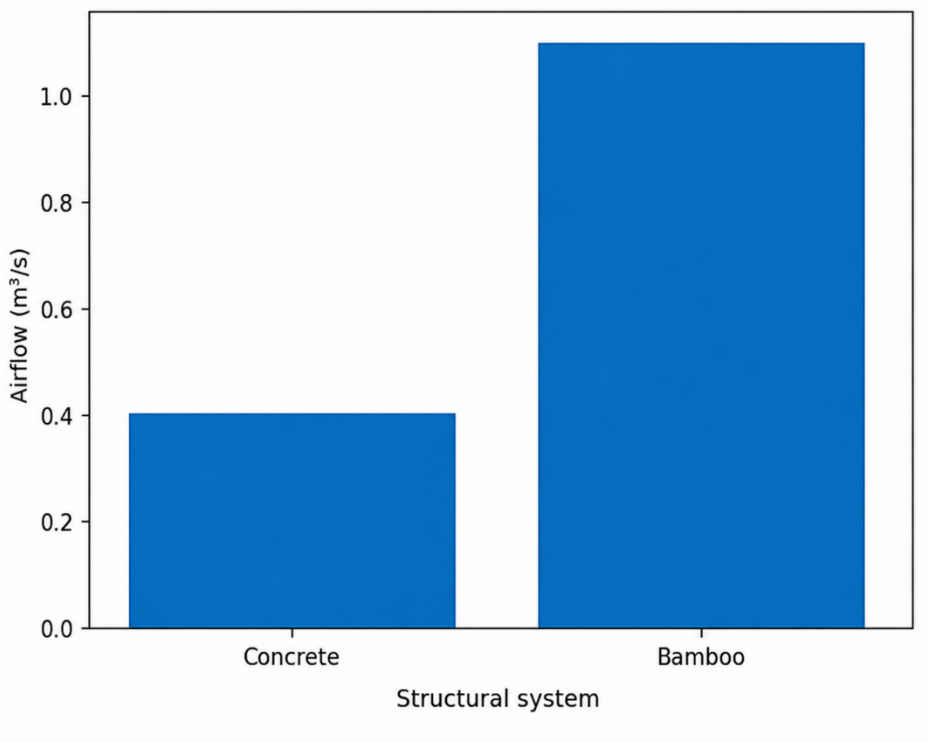


Figure 1. Comparison of passive airflow rates (m³/s) for concrete and bamboo structural systems. Source: Graph by the author.

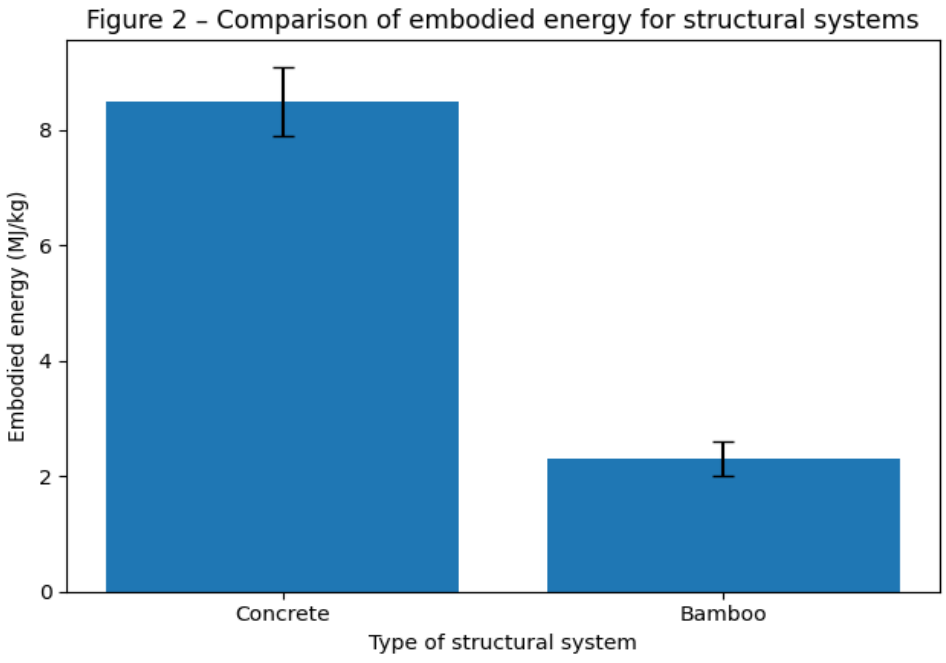


Figure 2. Comparison of embodied energy (MJ/kg) for concrete and bamboo structural systems. Error bars represent standard deviation. Source: Graph by the author.

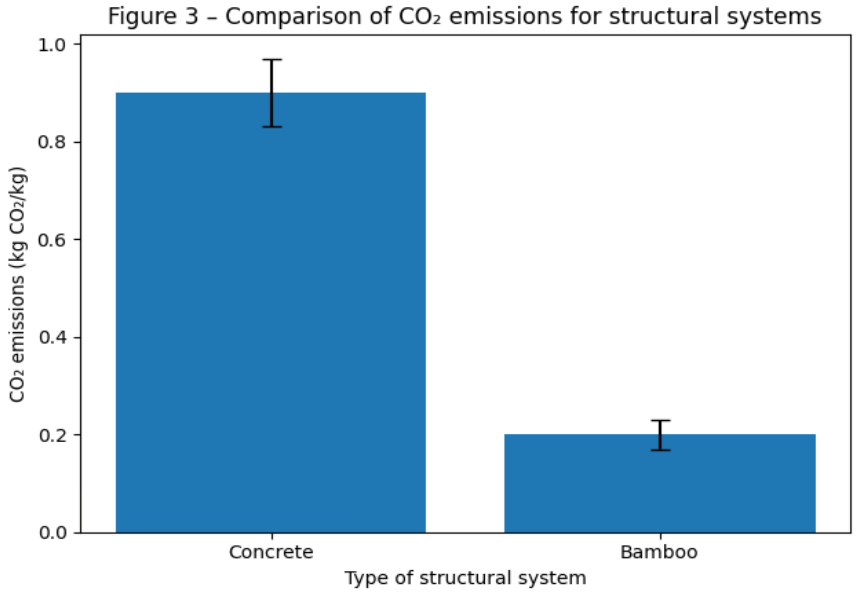


Figure 3. Comparison of CO_2 emissions (kg CO_2/kg) for concrete and bamboo structural systems. Error bars represent standard deviation. Source: Graph by the author.

These savings are associated with reduced use of industrial materials, shorter transportation distances, and compatibility with labor-intensive local construction practices. The bamboo-based system also demonstrated advantages in construction speed due to reduced structural mass, simplified assembly processes, and lower dependence on heavy industrial equipment.

Based on comparative construction scenarios, the estimated construction period for the bamboo prototype was 20–30 percent shorter than that of the reinforced concrete system. Overall, the results demonstrate that bio-based construction strategies can simultaneously improve environmental performance and reduce construction costs in tropical social housing contexts. A summary of the key performance indicators is presented in Table 1.

5. Discussion

The results demonstrate that the advantages of the bamboo-based system are not merely technical but systemic. Environmental, structural, thermal, and economic improvements emerge from coordinated integration rather than single-variable optimization. This integrative effect supports the conceptual premise of digital vernacular as a multi-scalar design framework capable of linking material ecology, computational design, and climatic adaptation.

5.1. Beyond material substitution

The observed reduction of approximately 65 percent in embodied carbon confirms the significant mitigation potential of renewable structural materials in tropical housing. However, the additional reduction of 12–18 percent achieved through parametric structural calibration indicates that digital design tools function as an environmental multiplier rather than simply enabling material substitution.

These findings challenge simplified narratives that frame sustainable construction as a binary transition from industrial to natural materials. Instead, they suggest that meaningful environmental improvements arise when material ecology is combined with computational optimization. Digital modeling enables more precise structural calibration, reducing excessive safety factors traditionally applied to biological materials.

Thus, sustainability gains are achieved not only by replacing concrete with bamboo but also by integrating bio-based materials within digitally optimized structural systems. The environmental advantages of bamboo-based systems may become even more significant when end-of-life scenarios are considered. Unlike reinforced concrete, which typically requires energy-intensive demolition and recycling processes, bamboo materials possess partial

Table 1. Comparative performance of reinforced concrete and bamboo structural systems

Parameter	Reinforced concrete	Bamboo system	Improvement
Airflow (m^3/s)	0.3–0.5	0.9–1.3	↑ 2–3×
Indoor Temperature (°C)	34–35	29–31	↓ 3–5 °C
Comfort (%)	32–38	58–64	↑ ~2×
Carbon (kg CO_2e/sqm)	420–460	150–170	↓ ~65%
Cost (USD/sqm)	520–560	290–340	↓ 25–40%

Note: The similarity between the reinforced-concrete values for embodied carbon and construction cost is coincidental and results from independent comparative modeling datasets.

biodegradability and may support lower-impact disposal or material reuse pathways within circular construction systems.

Consequently, inclusion of end-of-life phases in future LCAs may further widen the eco-efficiency gap between bamboo and conventional concrete construction. At the same time, bamboo-based construction systems also introduce important trade-offs. Although environmental performance improves significantly, broader implementation may require additional treatment processes, quality-control procedures, and specialized technical expertise, potentially increasing construction complexity in certain contexts.

5.2. Territorial implications

The transition from reinforced concrete to bamboo structural systems has broader territorial implications. In many regions of Latin America, cement production is centralized and dependent on long-distance supply chains and energy-intensive processes.

In contrast, bamboo can be harvested and processed within localized production networks. (Vogtländer *et al.*, 2010; Geissdoerfer *et al.*, 2017). The use of locally sourced biological materials reduces transportation-related emissions and supports regional economic activity. This shift represents a transformation from centralized industrial production toward localized material cycles. Accordingly, decarbonization should be understood not only as a technological transition but also as a territorial reconfiguration of construction material flows.

5.3. Informality and institutional integration

Another critical dimension concerns the relationship between vernacular construction practices and formal building regulations. In many tropical regions, including coastal Ecuador, a substantial portion of housing is constructed incrementally outside formal regulatory systems.

Despite its demonstrated structural capacity, bamboo construction is often associated with informal building traditions. The integration of digital structural calibration provides a potential bridge between vernacular knowledge and contemporary engineering standards. Traditional bamboo housing in many tropical regions commonly relies on empirical construction practices using locally available untreated culms without digital calibration or structural optimization.

The proposed digitally calibrated system differs in that it integrates measured geometric data into computational verification procedures, enabling improved material efficiency, more reliable structural consistency, and compatibility with contemporary engineering standards. By quantifying structural performance through computational modeling, natural materials can meet institutional verification requirements without compromising their ecological advantages.

This approach challenges the conventional dichotomy between "informal vernacular" and "formal engineered" construction systems. The Chinese experience with engineered bamboo systems also demonstrates how regulatory adaptation and institutional standardization can facilitate the transition of bamboo construction from vernacular practice to formally recognized structural technology (Sharma *et al.*, 2015).

The development of standardized engineered bamboo products, certification procedures, and national construction initiatives in China may therefore provide a useful reference model for overcoming the perception of bamboo as an "informal" material within Latin American housing systems.

5.4. Climate vulnerability and health

The observed reduction of 3–5 °C in indoor temperatures

has implications beyond thermal comfort. In low-income settlements where mechanical cooling is economically inaccessible, passive ventilation directly influences heat stress exposure and indoor air quality.

As climate change intensifies extreme heat conditions, material selection and building design become critical public health factors. Bio-based, permeable systems aligned with passive ventilation strategies can simultaneously reduce carbon emissions and enhance climate resilience.

5.5. Relation to Chinese bio-based architecture

Recent developments in China demonstrate how bio-based materials can be successfully integrated into contemporary architectural practice through industrial processing and digital fabrication technologies. These developments are also aligned with broader rural revitalization and sustainable construction policies implemented across China (Sharma *et al.*, 2015).

Engineered bamboo systems, such as Glubam, laminated bamboo composites, and Scrimber, illustrate the transformation of traditional biological resources into standardized structural materials capable of meeting modern engineering requirements. Recent experimental and applied projects in China also demonstrate the feasibility of multi-storey engineered bamboo structures, particularly when laminated bamboo composites and hybrid structural systems are used.

These developments indicate that bamboo construction is not limited to low-rise vernacular housing but may also support larger and more structurally demanding architectural applications. Experimental applications in tropical and subtropical regions of China, including Yunnan and Guangxi, have shown that bamboo construction can achieve high structural performance while maintaining low environmental impact (Sharma *et al.*, 2015; Vogtländer *et al.*, 2010). These developments are closely linked to national initiatives promoting bamboo as a substitute for carbon-intensive materials such as steel and concrete.

The results obtained in this study are consistent with these advancements. The bamboo-based system demonstrates improved eco-efficiency, reduced embodied carbon, and enhanced thermal performance, confirming that bio-based structural solutions can operate effectively within both vernacular and technologically advanced construction frameworks.

The digital vernacular framework proposed in this research provides a conceptual bridge between Latin American and Chinese approaches. While Chinese advancements emphasize industrial processing and standardization, Latin American traditions contribute long-established climatic adaptation strategies and locally grounded construction practices.

This comparison highlights the potential for cross-regional knowledge transfer and South–South collaboration in sustainable architecture. Integrating computational design with bio-based materials enables the development of scalable, climate-responsive housing solutions applicable across diverse tropical contexts.

5.6. Scalability and future research

Although the results are based on a single housing prototype, the proposed methodological framework is transferable to other tropical regions with similar climatic and material conditions. However, broader implementation of bio-based structural systems requires regulatory adaptation, development of industrial processing infrastructure, and technical training of construction professionals. Without these supporting conditions, such systems may remain limited to experimental applications.

Additional uncertainty is associated with the long-term durability of bamboo materials under highly humid tropical conditions. Although treated bamboo systems may demonstrate substantial durability under humid tropical conditions, long-term comparative performance relative to reinforced concrete structures was not experimentally evaluated within the scope of this study.

Factors such as biological degradation, moisture exposure, maintenance requirements, and the effectiveness of protective treatments should therefore be investigated through long-term monitoring studies. Variability in biological material properties may also influence structural consistency at larger construction scales.

Future research should focus on long-term performance monitoring of bamboo-based housing, expanded LCAs that include operational phases, and the development of standardized design guidelines to support wider regulatory acceptance.

5.7. Policy and implementation implications

The broader implementation of low-carbon bamboo housing systems requires coordinated institutional and industrial support. Several practical measures may facilitate wider adoption. First, national building regulations should incorporate standardized design guidelines and verification procedures for engineered bamboo systems. Regulatory recognition is essential for integrating bamboo construction into formal housing programs. Second, investment in localized bamboo processing infrastructure could improve material quality consistency, strengthen regional economic

development, and reduce transportation-related emissions. Third, technical education and professional training programs are necessary to support architects, engineers, and construction workers in applying computational design tools and bio-based construction methods. Finally, public housing policies in tropical regions should promote passive climatic design strategies and low-carbon material systems through financial incentives, pilot projects, and sustainability-oriented procurement frameworks.

6. Conclusion

This study demonstrates that integrating parametric design, engineered bamboo systems, and passive climatic strategies can provide a viable framework for low-carbon tropical social housing. A comparative analysis between a reinforced concrete baseline and a bamboo-based alternative, applied to a 54 sqm housing prototype in coastal Ecuador, demonstrates that sustainable housing solutions emerge from the integration of material ecology, digital structural optimization, and passive climatic design.

The results show that the bamboo-based system significantly reduced embodied carbon emissions, achieving approximately 65 percent lower values compared with conventional reinforced concrete construction within the A1–A5 life-cycle boundary. In addition, parametric structural calibration reduced material redundancy by 12–18 percent, further improving the eco-efficiency of the construction system.

Beyond environmental performance, the bamboo-based system enhances passive thermal comfort in humid tropical climates. Improved natural ventilation and a lightweight structural configuration contributed to a reduction in indoor temperatures by 3–5 °C compared with the reinforced concrete scenario. These findings highlight the importance of integrating structural material selection with passive climatic strategies, particularly in low-income housing contexts where mechanical cooling is limited.

The results also demonstrate clear economic advantages. The bamboo structural system reduced construction costs by 25–40 percent due to lower reliance on industrial materials, shorter transportation distances, and compatibility with local labor practices.

A key contribution of this research is the development of the digital vernacular framework, which integrates vernacular material knowledge with parametric design and circular bio-material strategies. This framework demonstrates how computational tools can enable natural materials to meet contemporary engineering and regulatory requirements while preserving their ecological benefits.

Furthermore, positioning the Latin American case study within the context of Chinese advancements in engineered bamboo construction highlights the potential for South–South knowledge exchange. Chinese innovations in engineered bamboo provide insights into industrial processing and standardization, while Latin American traditions offer valuable expertise in climate-responsive design for tropical environments (Sharma *et al.*, 2015).

Several limitations should be acknowledged. The findings should be interpreted as a comparative exploratory assessment rather than as a fully validated predictive model for large-scale implementation. The environmental assessment was restricted to A1–A5 stages, excluding operational and end-of-life impacts. Thermal performance was evaluated using simplified modeling assumptions, and structural calibration was based on representative samples rather than full-scale prototypes. Furthermore, extreme wind resistance and long-term durability performance of the bamboo-based system were not experimentally assessed and remain important directions for future investigation.

Future research should extend life-cycle boundaries, implement full-scale experimental validation, and develop regulatory frameworks supporting wider adoption of bio-based construction systems. Additional research using full CFD simulations may also provide a more precise evaluation of airflow dynamics, humidity distribution, and passive thermal comfort performance in tropical bamboo housing systems. Comparative studies across different tropical regions, including Latin America and China, would further clarify the scalability of the digital vernacular approach.

Furthermore, the results reinforce the applicability of Chinese advancements in engineered bamboo construction within tropical social housing contexts. The integration of industrial bamboo technologies with vernacular design principles demonstrates strong potential for cross-regional adaptation and supports the development of globally scalable low-carbon construction strategies. The proposed framework demonstrates strong potential for practical implementation in climate-vulnerable regions and contributes to global decarbonization efforts in the building sector.

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Not applicable.

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Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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