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Bamboo as a Renewable Material for Sustainable Building Practices in Guatemala

By

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Abstract

Bamboo is a fast-growing renewable resource with diverse applications in sustainable construction. Its ability to capture and sequester carbon, combined with its rapid regeneration cycle, positions it as an environmentally friendly material. However, its adoption faces challenges due to limited awareness of its viability as a safe structural material. In Guatemala, there are approximately 12,000 hectares of bamboo, with species such as Guaduaangustifolia, Dendrocalamus asper, and Gigantochloaverticillata, which exhibit mechanical properties suitable for construction. Some studies have shown that bamboo can absorb up to 54.3 tons of carbon during a six-year growth cycle, contributing to climate change mitigation. The physical and mechanical properties of bamboo vary by species. The three forest-managed species in Guatemala demonstrate good compressive and shear strength, although shear resistance is comparatively lower. In particular, the low shear strength of internode sections requires optimized structural designs. Nevertheless, its high tensile strength makes it ideal for structures subjected to bending. This article examines these aspects and highlights bamboo's potential as a structural alternative in civil engineering and architecture, promoting its use in sustainable building practices and its integration into Guatemala's construction regulations.

Keywords:

Bamboo, sustainable construction, mechanical properties, climate change mitigation.

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1. Introduction

Bamboo is the fastest-growing and most multifunctional plant on Earth. Throughout history, it has played a significant role in the daily lives of millions of people—particularly in tropical countries—providing a wide array of environmental, social, cultural, and economic benefits. As a member of the subfamily Bambusoideae within the Poaceae family, bamboo is primarily found in tropical and subtropical regions of Asia, the Americas, and Africa. Although Europe has no native bamboo species, the rest of the world hosts remarkable diversity of this resource. Approximately 123 genera and over 1,500 species have been identified worldwide (Ahmad et al., 2021).

Despite its abundance and versatility, bamboo remains an underutilized or undervalued resource, especially in tropical and subtropical regions. Countries rich in bamboo, such as Guatemala, could harness its diverse properties to address and mitigate climate change, improve air quality, and deliver valuable ecosystem services, as well as generate new sources of income for rural populations. However, two major obstacles hinder its development: a general lack of awareness about its benefits among policymakers (including academia, the business sector, and society at large) and its classification under forestry regulations, which complicates its sustainable use (International Network for Bamboo and Rattan –INBAR–, 2014).Bamboo has been used since ancient times to improve human quality of life. Its flexibility, adaptability, and versatility have made it an essential material for construction—from furniture to bridges and buildings—demonstrating its practical value across a wide range of applications (Poveda, 2011). This versatility is a key feature that allows bamboo to meet various structural demands, making it an ideal and reliable material for sustainable construction.

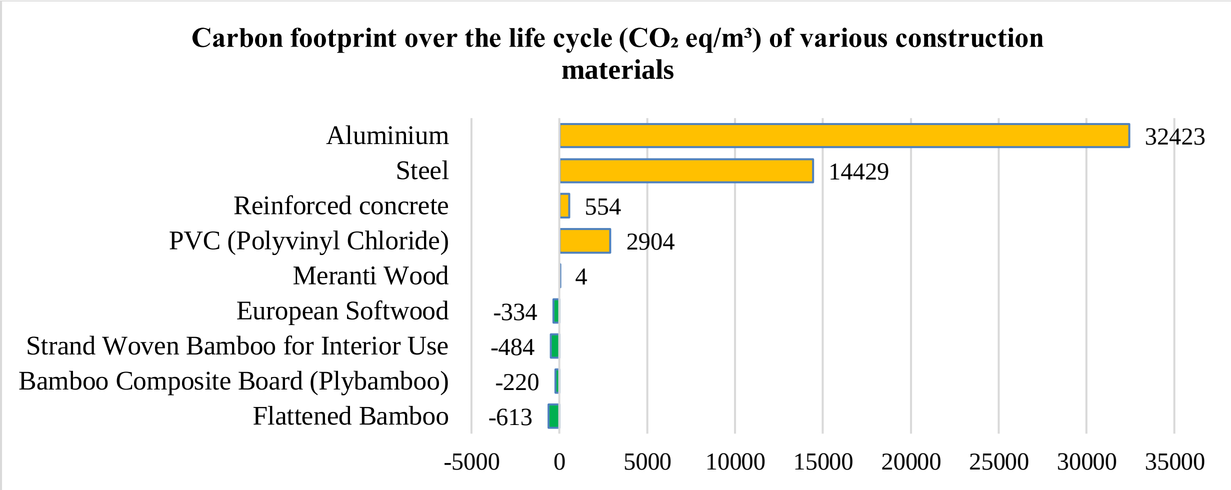
Guatemala, with its diverse topography and geographic location in the subtropical zone of the Northern Hemisphere, holds significant potential to become a major bamboo producer. The country possesses land with ideal agroclimatic conditions for bamboo growth, positioning it as both a domestic and international supplier (CONADEA & GTA-BAMBÚ, 2022). It is estimated that Guatemala has around 12,000 hectares of bamboo, including species such as Bambusa vulgaris, Guaduaangustifolia, Dendrocalamus asper, and Gigantochloaverticillata, all of which display mechanical properties suitable for construction and industrial applications (CONADEA & GTA-BAMBÚ, 2022).This article explores the advantages of bamboo as a construction material, emphasizing the reasons for its classification as a sustainable resource. It also analyzes its physical and mechanical properties, highlighting its structural viability and potential as an efficient and eco-friendly alternative in the fields of civil engineering, structural engineering, and architecture.

2. Carbon Sequestration and Energy Potential of Bamboo: A Sustainable Perspective

Bamboo is the only natural material that produces five times more oxygen than any other plant, working in constant synergy with the environment. This is due to its self-regenerating capacity, which ensures continuous carbon dioxide (CO_2) capture and fixation. Moreover, this plant-based material retains and stores CO_2 within its structure, even after being processed into construction elements (Muscio, 2020).

Figure 1.

Carbon Footprint Comparison of Various Construction Materials



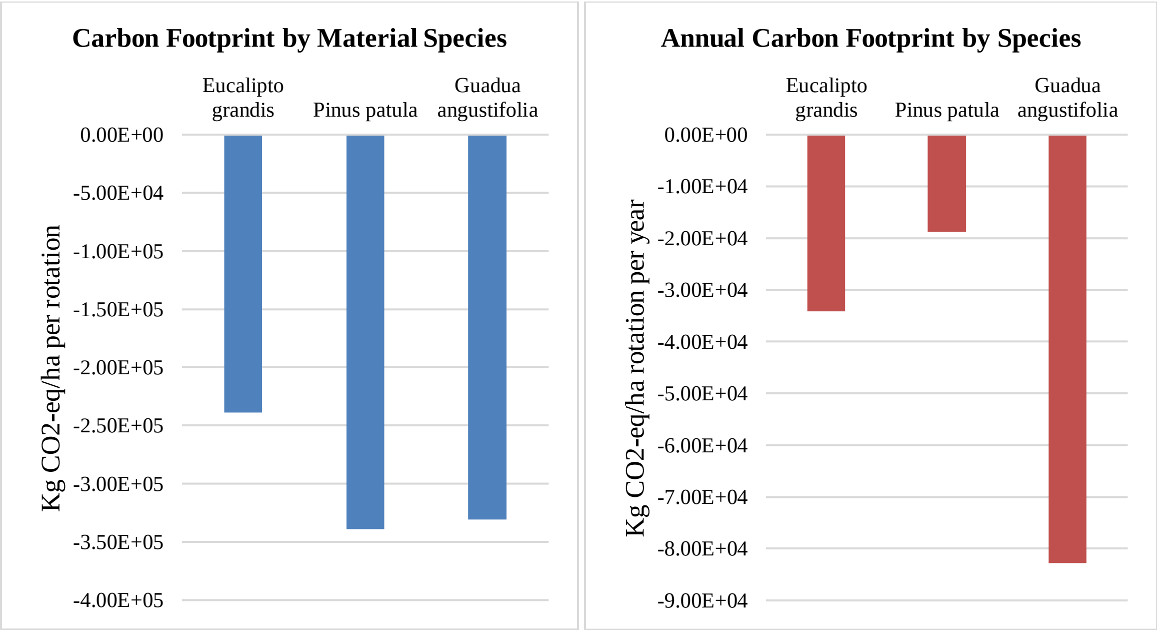
*Note.*The graph illustrates the carbon footprint, highlighting that bamboo-based materials exhibit a negative carbon footprint.Source: International Network for Bamboo and Rattan – INBAR– (2014).

As illustrated in Figure 1, bamboo and its derivatives possess a negative carbon footprint. This means they not only reduce greenhouse gas (GHG) emissions in the atmosphere, but also yield a net balance of carbon capture or removal. In other words, more carbon is sequestered than emitted.

Martínez et al. (2018), in their study Carbon footprint of the life cycle of commercial forest plantations (Eucalyptus grandis, Pinuspatula) and protective forests (Guaduaangustifolia Kunth) in Colombia, analyzed the total carbon footprint for each plantation type and reported negative emission flows. This confirms atmospheric CO_2 absorption when considering both fixation rates and maintenance processes. Among the evaluated species, Pinuspatula showed the highest total carbon sequestration, while GuaduaangustifoliaKunth stood out in terms of annual fixation rate.

Figure 2.

Comparative carbon footprint charts for various forest and herbaceous species



*Note.*These charts show that the carbon footprint for Eucalyptus grandis is -239 t/ha over a 7-year period, for Pinuspatula is -339 t/ha over 18 years, and for Guaduaangustifolia Kunth is -331 t/ha over 4 years. Source: Martínez et al. (2018).

The estimated carbon fixation for Guaduaangustifolia over a six-year growth cycle is 54.30 tons, of which 10.80 tons (19.90%) are stored in the rhizome and 43.50 tons (80.10%) in the aerial portion of the plant. In the early growth stages, the combined contribution of the rhizome and culm represents 50% of total biomass, while after six years, this share increases to 90% (Torres et al., 2019).

Additionally, bamboo can be used to produce firewood and charcoal for cooking and heating, as well as for electricity generation through biomass gasification technologies. Bamboo charcoal has a calorific value comparable to wood charcoal but is significantly less polluting. The International Network for Bamboo and Rattan (INBAR, 2014) has demonstrated that using bamboo for charcoal production can reduce pressure on other forest resources, thereby preventing deforestation and the release of stored carbon into the atmosphere. Bamboo is also a viable alternative to fossil fuels, both as a combustible and as a soil-replenishing fertilizer for land restoration and conservation.

3. Innovative Applications in Architecture, Engineering, and Construction

Bamboo has emerged as a sustainable alternative in construction due to its combination of mechanical strength, low weight, and rapid renewability.This section presents various test results conducted in Guatemala on three structural bamboo species: Dendrocalamus asper, Guaduaangustifolia, and Gigantocloaverticillata. These data allow for an evaluation of their suitability for construction applications, taking into account factors such as density, compressive strength, bending strength, and shear strength.Additionally, certain bamboo construction applications implemented both in Guatemala and in other bamboo-producing countries are presented.

3.1. Physical and Mechanical Performance of Bamboo: Comparative Analysis of Structural Species

The following is a summary of laboratory test results conducted by Calo (2018) on the three most commonly used structural bamboo species in Guatemala.

Table 1.

Physical and Mechanical Properties of Three Structural Bamboo Species in Guatemala

Type of Test	Dendrocalamus Asper	Guadua Angustifolia	Gigantochloa Verticillata
Green moisture content (%)	40.75	79.49	48.91
Dry moisture content (%)	17.87	14.15	15.09
Green specific weight (N/m³)	8477.10	8279.88	8009.64
Dry specific weight (N/m³)	6949.99	5636.90	4636.36
Green density (g/cm³)	0.87	0.84	0.82
Dry density (g/cm³)	0.70	0.58	0.47
Volumetric shrinkage (%)	3.96	14.41	5.42
Water absorption (%)	27.85	32.29	26.96
Hardness (Kg)	366.76	240.91	326.58
Tension perpendicular to fiber (kg/cm²)	6.16	8.80	5.03
Compression with one node (kg/cm²)	147.60	101.72	145.00
Compression without node (kg/cm²)	112.76	101.68	115.23
Compression with two nodes (kg/cm²)	118.23	85.21	115.79
Shear without nodes (kg/cm²)	90.18	73.08	91.93
Shear with nodes (kg/cm²)	79.25	63.50	67.69
Modulus of rupture (kg/cm²)	768.02	490.37	835.83
Modulus of elasticity (kg/cm²)	95308.72	66331.68	63290.94
Maximum deflection (cm)	1.8	1.8	3.2

Note. Physical and mechanical properties of bamboo, sourced from Calo (2018).

Bamboo exhibits a remarkably variable mechanical performance depending on the species, with significant differences in its physical and mechanical properties.In the case of Dendrocalamus asper, Guaduaangustifolia, and Gigantocloaverticillata, notable contrasts can be observed in terms of density, mechanical strength, and dimensional stability—factors that are critical for structural applications.

One of the less favorable aspects of bamboo is its shear strength, which is particularly compromised in the absence of nodes. However, the nodal region significantly enhances this parameter, implying that the structural design of bamboo elements should consider configurations that optimize this feature, such as the use of double or triple culms. In the tests conducted by Calo (2018), Guaduaangustifolia exhibited the lowest shear strength, both with nodes (63.5 kg/cm²) and without nodes (73.08 kg/cm²), while Gigantocloaverticillata demonstrated better performance in this regard.

In terms of compressive strength, values are relatively high; although it is important to note that these measurements assume ideal conditions without buckling effects. If buckling occurs, the structural stability of bamboo could be compromised, making it advisable to use columns or pedestals composed of multiple culms to improve axial load performance. Among the analyzed species, Dendrocalamus asper and Gigantocloaverticillata show the highest compressive strengths, both with and without nodes, although the differences with Guaduaangustifolia are not particularly significant.

Tensile strength is one of bamboo's main mechanical advantages, with values significantly exceeding those of compression. Although specific experimental values for this property are not available for the species analyzed, previous studies have shown that tensile strength can be up to four times greater than compressive strength. However, given the complexity of executing joints subjected to tensile forces, it is recommended to design bamboo structures that work primarily under bending and compression loads.

The modulus of elasticity and bending capacity also vary among species. Dendrocalamus asper exhibits the highest stiffness, with a modulus of elasticity of 95,308.72 kg/cm², suggesting better performance in structures subjected to bending loads. However, Gigantocloaverticillata, despite having a lower modulus of elasticity, shows the highest modulus of rupture (835.83 kg/cm²), indicating a strong ability to absorb stress before failure.

Structurally, bamboo has greater strength in the outer cortex compared to the inner portion. Therefore, species with smaller diameters may display better bending properties due to a higher proportion of strong fibers in the cross-section, as seen in Guaduaangustifolia. Likewise, when stresses act perpendicular to the bamboo wall, its strength decreases considerably due to the tendency of its fibers to separate. This phenomenon also causes surface cracking in some species during drying, highlighting the importance of appropriate preservation and joint strategies to prevent premature failure of structural elements.

3.2. Architectural and Structural Applications

In the department of Sololá, expansion projects are currently being carried out in public educational institutions, featuring architectural designs developed by Architect Palacios. These infrastructures, funded through international cooperation from Germany, incorporate the use of bamboo as a sustainable structural material. The following images illustrate the application of bamboo in school buildings.

Figure 3.
Visual Documentation of Bamboo Use in Guatemalan Educational Infrastructure

Note. Primary school classroom at Tijobal Pa Kat Chabal CheraNabey School, located in the municipality of Sololá, department of Sololá, Republic of Guatemala. Photo by the authors.

In Guatemala, the use of bamboo for structural purposes is still not widely adopted; however, the myth that bamboo is unsuitable for infrastructure is gradually being dispelled. An example of this can be seen in Figures 3 and 4, where bamboo is used in combination with other materials to develop projects in the educational sector. Its properties play a fundamental role in the design and construction of these structures.

Figure 4.
Images of Structural Bamboo Applications in Educational Buildings in Guatemala

Note. Classrooms at Los YaxónNeboyá School, located in the municipality of Sololá, department of Sololá, Republic of Guatemala. Photo by the authors.

At the University Of San Carlos Of Guatemala, Herrera (2021) conducted a research project focused on the design, construction, and evaluation of a pedestrian bridge made from structural bamboo. The architectural structure, measuring 6.50 meters in length and 3.00

meters in width, was the subject of an in-depth analysis regarding its feasibility and performance.

Figure 5.
Images of Structural Bamboo Applications in Pedestrian Bridges

Note. Structural pedestrian bridges developed as part of a civil engineering thesis project at the Faculty of Engineering, University of San Carlos of Guatemala. Source: Herrera (2021).

The tests shown in Figure 5 were conducted at the Wood Technology Section of the Engineering Research Center at the University Of San Carlos Of Guatemala. These tests, performed on pedestrian bridges, yielded satisfactory results, even meeting the requirements established by the AASHTO standards of the United States for bridge design and construction. This demonstrates the properties of bamboo, not only as a sustainable and environmentally friendly material, but also as a structurally viable alternative.

Figure 6.
Images of Bamboo Structural Assembly for Vehicle Shelter Roofing

Note. Assembly of the bamboo structure for a vehicle parking roof, located at the facilities of the Wood Technology Section of the Engineering Research Center, University of San Carlos of Guatemala. Photo by the authors.

Another functional project involves a vehicle shelter roof (Figure 6) located within the Wood Technology Section. This structure has been in operation since 2018, thanks to the quality of the bamboo and the maintenance that has been provided over the years.

3.3. Notable Bamboo-Based Construction Projects

In 2008, architects JörgStamm and Xavier Pino, in collaboration with structural consultant Gerardo Castro, completed the design of a bridge in Cúcuta, Colombia, covering an area of 400 square meters. To mitigate the effects of weather conditions, a membrane roof was incorporated as a protective measure. The structural design of the project includes a load-bearing capacity of 500 kg/m², ensuring a projected service life of 30 years (Minke, 2012).

Figure 7.
Image of a Bamboo Pedestrian Bridge in Cúcuta, Colombia

Note. The image shows a structure built using advanced engineering techniques—a pedestrian bridge constructed with Guaduaangustifolia bamboo, which interacts synergistically with other construction materials to optimize its structural strength and functionality (Minke, 2012).

The bridge designed by architects JörgStamm and Juan Carlos Sanz, with structural calculations by Hermann Lehmann, was completed in 2005 at an estimated cost of USD 40,000. It spans 30 meters with a clear width of 3 meters. Its construction involved the use of 600 culms of Guaduaangustifolia, with diameters ranging from 10 to 14 cm. The structural design was calculated to support a load of 500 kg/m, a wind force of 15 tons, and an estimated service life of 30 years.

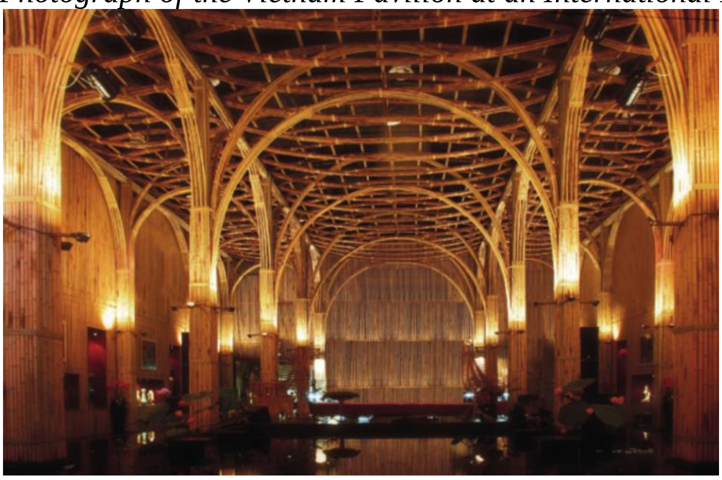
Naturally curved culms were selected to form the arches, ensuring efficient load distribution. The compressive forces generated within the structure are transferred to a massive concrete foundation, providing overall stability. The bridge deck was constructed using concrete, while the roof is covered with terracotta tiles. The assembly process was completed within a period of three weeks (Minke, 2012).

Figure 8.
Photograph of a Guaduaangustifolia Bamboo Pedestrian Bridge in Cúcuta, Colombia

Note. Bamboo pedestrian bridge composed of reticulated bamboo elements and specialized structural techniques, such as arched components (Minke, 2012).

The following landmark project corresponds to the Vietnam Pavilion at Expo 2010, held in Shanghai, China. The pavilion was built using bamboo due to its low cost and reusability. A total of 80,000 bamboo culms, each 12 meters long, were bent and tied with ropes to form the exterior façade and inner courtyard. Inside, the suspended ceilings and column cladding were also made of bamboo, as were the decorative arches, which consisted of curved bamboo poles tied together. The species Bambusaoldhamii was sourced from Anji County in Zhejiang Province, China, a region known for its bamboo plantations. However, due to a lack of skilled labor in China, the construction was carried out by specialists from Vietnam (Minke, 2012).

Figure 9.
Photograph of the Vietnam Pavilion at an International Event in Shanghai, China



Note. Bamboo structure with diverse applications in an integrated project, highlighting its versatility in structural, ornamental, and artistic functions—demonstrating its ability to combine aesthetics and strength (Minke, 2012).

4. Concluding Synthesis

Bamboo stands out as a key natural resource for sustainable construction, owing to its rapid growth, carbon sequestration capacity, and versatility in a wide range of structural applications. Its potential to mitigate climate change and deliver valuable ecosystem services makes it an efficient alternative for civil and structural engineering—particularly in countries with favorable agroclimatic conditions, such as Guatemala.

Despite its evident advantages, bamboo remains underutilized in many regions, primarily due to limited awareness of its properties and a lack of regulatory frameworks that enable its proper use. While its physical and mechanical properties vary by species, they are generally robust enough to warrant consideration for sustainable construction. However, the low shear strength of some species—especially in internodal sections—has historically posed challenges. This has led to the use of specific bamboo varieties and the development of optimized structural designs that enhance both efficiency and safety.

In summary, bamboo holds tremendous potential to become a cornerstone material in sustainable construction. Its appropriate use depends on the establishment of regulatory frameworks that ensure quality and structural safety. Promoting its use through standardized norms and ongoing research can contribute significantly to sustainable development and climate change mitigation.

Based on the analysis presented, several actions are recommended to strengthen Guatemala's productive, scientific, economic, academic, and social sectors. These include encouraging the use of bamboo in sustainable construction, developing standardized regulations and certifications, promoting research and technological development, and providing governmental support through public policies that facilitate its implementation and expansion across the country.

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Supplementary Material

The dataset supporting the findings of this study has been provided by the authors and is available as supplementary material online.
File name: *Supplementary_Data_Bamboo_Guatemala.xlsx*
You can access it with the published article at
https://gphjournal.org/index.php/ssh/article/view/2012

Researchers are encouraged to use the dataset for non-commercial academic purposes, with proper citation of this article.