

Bamboo as a construction material: from plants to structures

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HIGHLIGHTS

- Life cycle review: from bamboo biology to structural use in buildings.
- LCAs indicate that bamboo buildings can achieve low or net-negative life cycle carbon outcomes under favorable assumptions.
- Compares round bamboo and engineered bamboo as structural products.
- Reviews treatments improving durability, dimensional stability, and fire safety.
- Identifies research gaps in design methods, long-term data, and LCA inventories.

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ABSTRACT

Amid the global push for sustainable construction, bamboo has been widely studied as a rapidly renewable, high-performance building material. This paper reviews the published literature on bamboo's journey from plant to structural component. The review first examines the fundamental botanical characteristics of bamboo, explaining the relationship between its hierarchical structure—from molecular to cellular levels—and its mechanical properties. It then transitions to an analysis of sustainable forestry, harvesting practices, the structural uses of round bamboo, and the manufacturing processes for engineered bamboo products, such as glued laminated bamboo and bamboo scrimber. Critical performance challenges are addressed by evaluating modern treatment methods that enhance durability, dimensional stability, and fire resistance. Structural applications are explored in detail,

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covering traditional building typologies, innovative connection systems, and the emerging potential for bamboo in mid- and high-rise as well as long-span structures. The life cycle perspective is completed by examining end-of-life scenarios, including reuse, recycling, and energy recovery. Ultimately, the review situates bamboo within the global context by examining resource distribution, trade, and the policy frameworks required to promote its widespread adoption. By consolidating research across multiple disciplines, this paper highlights the significant potential of bamboo to contribute to a low-carbon built environment. It concludes that a holistic, science-based approach is essential for overcoming remaining challenges and fully integrating this versatile material into modern construction practices.

1. Introduction

1.1. Background and motivation

The escalating urgency of addressing climate change mandates a fundamental transformation within the construction industry, a primary contributor to global greenhouse gas emissions [1]. In response, the search for sustainable alternatives to carbon-intensive materials, such as steel and concrete, has intensified, placing a renewed focus on bio-based resources. Among these, timber has attracted considerable attention, particularly for high-rise building construction [2]. However, achieving a sustainable built environment requires a broader material palette that considers not only carbon sequestration but also resource renewability, processing efficiency, and life cycle impacts [3]. In this context, bamboo emerges as a promising candidate, offering a unique combination of rapid growth [4] and mechanical properties [5].

The use of timber in structural engineering is ancient, with evidence of hominins building with wood dating back at least 476,000 years [6]. In contrast, the technological foundations for bamboo construction, such as processing it into fiber for ropes, emerged around 39,000 years ago [7], with direct evidence of its use in wattle-and-daub housing dating back to 4500 years ago in Neolithic China [8,9].

Bamboo is a fast-growing perennial grass classified under the Poaceae family, with over 1600 species worldwide [10]. It has been utilized in construction for millennia, especially in developing countries [11], but its potential in modern architecture has only begun to be realized in recent decades. Bamboo's rapid growth cycle makes it a highly sustainable alternative to traditional wood, while its strength-to-weight ratio, which surpasses that of most timbers, makes it suitable for lightweight yet structurally robust buildings [12]. The material's intrinsic appeal lies in its rapid renewability and exceptional strength, rendering it an environmentally conscious alternative to conventional building materials [13,14]. As noted by Asif [15], both wood and bamboo are at the "heart of modern construction owing to their versatility, abundance in nature, and environmental friendliness". Crucially, the limitations of round bamboo—such as irregular dimensions and variability in mechanical properties—are now gradually being overcome through tailored design approaches and industrial processing [16–21]. Engineered bamboo products, including glued laminated bamboo and bamboo scrimber [22], provide consistent mechanical properties that are comparable to, and in some cases exceed, those of structural timber [23]. This allows them to be designed and specified using established engineering principles, positioning them as viable timber alternatives in mainstream construction.

Construction-grade bamboo and its engineered derivatives are among the highest-value outputs from bamboo cultivation, significantly contributing to agroforestry-based economies [11,14,24]. Bamboo's rapid growth and regenerative harvesting make it a highly renewable resource. Furthermore, its life cycle extends beyond primary structural use; manufacturing co-products and end-of-life materials can be repurposed for secondary applications such as furniture, bioenergy, and biodegradable composites, ensuring continuous economic and ecological benefits within a circular economy framework [25,26].

Recent reviews have examined bamboo construction materials and engineered bamboo products from sustainability and structural perspectives [14,23,27], addressing primarily material-level performance or specific applications in isolation. This paper offers an extensive overview of bamboo as a structural material, employing an integrated life cycle framework that spans from the species' biological characteristics to its disposal and end-of-life pathways. Drawing inspiration from the integrated approach of "The Wood From the Trees: The Use of Timber in Construction" by Ramage et al. [2], it provides a broad yet detailed overview of the current state of the art. Through this multifaceted analysis, this review seeks to move bamboo beyond its usual image as a niche material used only in traditional architecture, and instead highlight it as a practical, competitive option for contemporary, sustainable building. By consolidating current knowledge, addressing key challenges, and highlighting ongoing innovations, it seeks to foster a deeper understanding of bamboo's life cycle performance and to support wider adoption of bamboo in environmentally responsible construction practices.

1.2. Carbon footprint and life cycle assessment framework for bamboo in construction

Fig. 1 shows the closed-loop carbon cycle of bamboo. The cycle begins as growing bamboo sequesters atmospheric CO₂, storing carbon in its biomass. This stored carbon is then transferred into durable construction products, creating a long-term biogenic carbon sink during a building's service life. At the end-of-life stage, a cascading utilization strategy is prioritized: bamboo components can ideally be reused or recycled to extend the carbon storage period. When these options are exhausted, energy recovery from bamboo co-products returns biogenic CO₂ to the atmosphere, completing the natural cycle without directly releasing fossil carbon from the bamboo biomass itself. Concurrently, the perennial rhizome system ensures continuous regeneration of the bamboo stand, facilitating ongoing carbon sequestration. This integrated process—from growth and harvesting to cascading utilization and regeneration—forms a self-sustaining, regenerative carbon cycle, highlighting bamboo's significant potential to contribute to the decarbonization of the built environment.

The carbon balance quantifies the total emissions and removals of CO₂ associated with a product system over its life cycle. This is usually assessed within the broader framework of life cycle assessment (LCA), which comprises four main phases: (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation, following ISO 14,040 [28]. For buildings, the European standard EN 15,978 [29] further organizes the life cycle into modules: product stage (A1–A3), construction process stage (A4–A5), use stage (B1–B7), end-of-life stage (C1–C4), and beyond-the-system-boundary benefits and loads (D).

LCA studies provide evidence for the comparatively low environmental impact of bamboo structures [26,30–41]. It should be noted that the carbon-accounting studies synthesized in this review are interpreted primarily within a conventional static LCA framework, consistent with the module-based building assessment structure of EN 15,978 [29]. Dynamic LCA may provide additional insight into the timing of carbon

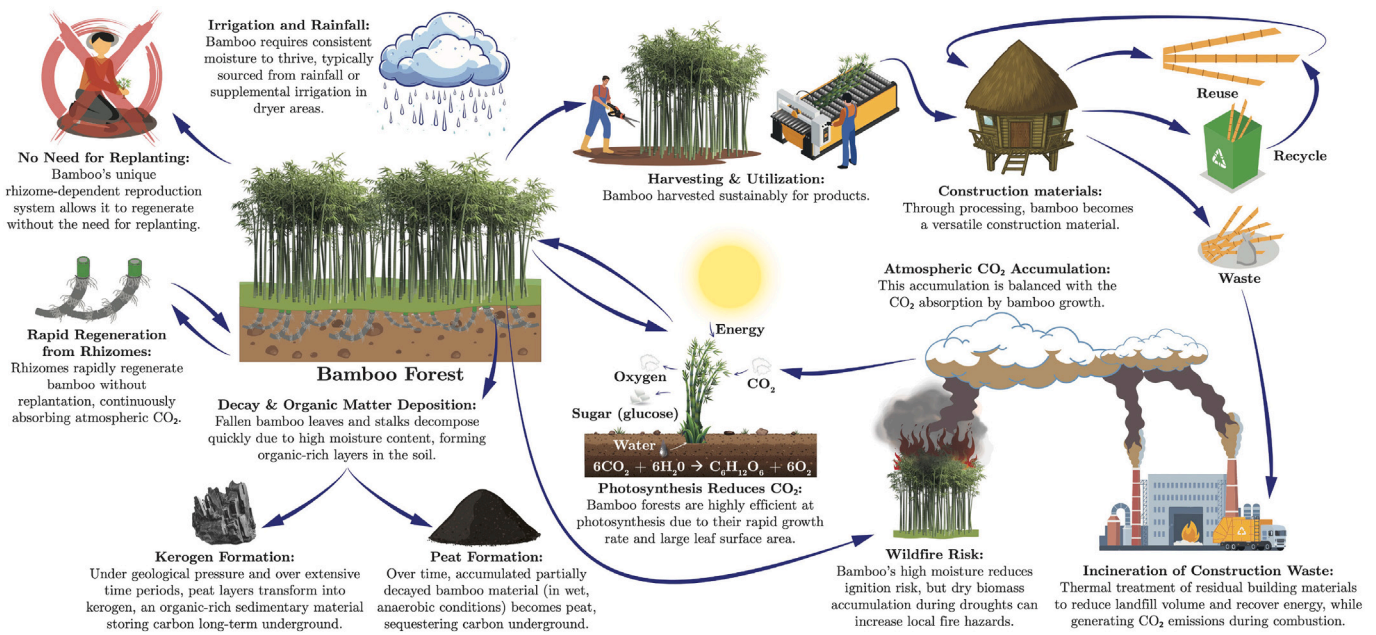


Fig. 1. Schematic illustration of the carbon cycle within a bamboo forest and its connection to the construction industry.

sequestration, storage, and delayed release for bio-based materials, but it is not yet the dominant methodological basis of the bamboo LCA literature reviewed here [42]. As an illustrative example, Escamilla et al. [26] compared the cradle-to-construction CO₂ balance of bamboo-based and conventional building systems by accounting for the CO₂ captured, stored, and emitted during material production (discussed in Section 3.2.2). In this balance, positive values indicate net CO₂ emissions, whereas negative values indicate that stored biogenic carbon exceeds production-related emissions. As shown in Fig. 2, brick and concrete-based systems show clearly positive CO₂ balances. For the best-case scenario (lower whisker in the bar), both bamboo-based construction systems present a negative CO₂ balance, indicating that the implementation of these options holds the potential to reduce the levels of atmospheric CO₂. The engineered bamboo building systems, however, show positive CO₂ balances in low-performance scenarios (higher whiskers in the bar), which indicates that part of the carbon-storage benefit of bamboo material can be offset by the additional energy demand for industrial processing.

The LCA framework introduced here provides a unifying lens for the remainder of this review. At a high level, the paper's organization maps directly to the building life cycle, as summarized in the synthesis table below (Table 1).

1.3. Research questions and structure of the paper

Building on the motivation outlined above and the LCA framework introduced in Section 1.2, this review is organized around a set of overarching research questions that bridge scales from plant biology to structural systems and policy.

1. Under which conditions can bamboo-based buildings achieve potentially net-negative life cycle carbon outcomes, and how do system boundaries, service life, and end-of-life scenarios influence this outcome?
2. How do bamboo's botanical and hierarchical structural features translate into mechanical properties relevant for structural applications, and how do these compare with those of conventional bio-based and mineral construction materials?
3. What are the implications of different forestry practices, harvesting regimes, and processing routes (from raw bamboo culms to

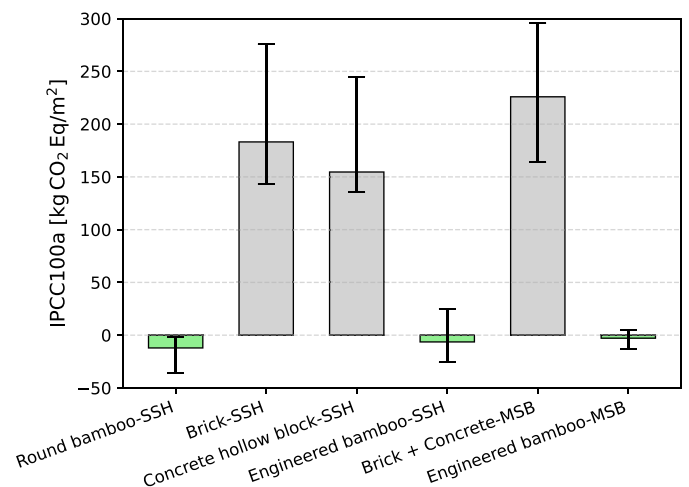


Fig. 2. Comparison of cradle-to-construction CO₂ balance (evaluated using IPCC100a method [43]) between bamboo-based and conventional building systems. The balance accounts for biogenic carbon storage in bamboo materials. SSH: single-story house; MSB: multi-story building. Data adapted from Escamilla et al. [26].

processed round bamboo or engineered bamboo products such as glued laminated bamboo and bamboo scrimber) for the environmental, mechanical and durability performance of bamboo construction systems?

4. Which structural systems, connection technologies, and design approaches are currently available for bamboo in low-, mid- and high-rise, as well as long-span applications, and what evidence exists regarding their long-term performance, safety, and serviceability?
5. How do fire performance, durability, indoor environmental quality, digital design tools, and policy and market frameworks affect the large-scale adoption of bamboo in the built environment, and where are the most critical knowledge gaps for future research?

Table 1
Mapping of review topics to EN 15,978 [29] life cycle modules.

Life cycle stage (EN 15978)	Corresponding manuscript sections	Key topics addressed
Product stage (A1–A3)	Sections 2, 3, and 4	Bamboo biology, forest management, harvesting, grading, and early processing
Construction process stage (A4–A5)	Section 5	Construction typologies, structural assemblies, and connection techniques
Use stage (B1–B7)	Sections 5, 6 and 7	Structural behavior, mechanical properties, indoor environmental quality, fire resistance performance and durability
End-of-Life stage (C1–C4)	Section 7	Waste treatment scenarios
Beyond system boundary (Module D)	Section 7	Circular economy applications, reuse, recycling, and energy recovery

To address these questions, the paper follows a logical progression from the microscopic to the macroscopic. Section 2 examines the biology and hierarchical structure of bamboo plants, establishing links between anatomy and mechanical properties. Section 3 reviews global bamboo forests, resource availability, and associated ecosystem services, including carbon sequestration. Section 4 discusses the harvesting, processing, and manufacturing of round bamboo and engineered bamboo products, together with treatments that enhance durability and fire performance. Section 5 focuses on structural applications and connection systems in buildings and civil engineering works, including emerging mid- and high-rise as well as long-span solutions. Section 6 evaluates the indoor environmental quality of bamboo-based constructions. Section 7 addresses fire resistance, durability, and end-of-life scenarios. Section 8 examines the policy, standardization, and market aspects governing the deployment of bamboo in construction. Finally, Section 9 synthesizes the main findings related to these research questions and outlines the priorities for future research and practice.

2. Bamboo: the plant

2.1. Bamboo variation

Bamboo, classified within the subfamily Bambusoideae of the vast Poaceae grass family, constitutes a remarkably diverse group of perennial woody grasses. This subfamily encompasses approximately 121 genera and 1662 species, which thrive primarily in tropical and subtropical regions, although some species have adapted to temperate climates [44]. Notably, bamboo species are endemic to all continents except Europe and Antarctica [45].

Among the Poaceae family, bamboo is distinctive as the only major lineage that has undergone significant diversification within forest ecosystems. The Bambusoideae subfamily is currently organized into three tribes, reflecting its main evolutionary divisions: Arundinarieae, comprising temperate woody bamboos (533 species); Bambuseae, which includes tropical woody bamboos (784 species); and Olyreae, consisting of herbaceous bamboos (122 species) [46].

Bamboo is among the largest and most structurally complex members of the grass family. Its evolutionary trajectory is closely intertwined with the broader diversification of grasses, a process initiated during the late Cretaceous period and continuing into the early Paleogene [47]. Phylogenetic analyses suggest that bamboo diverged from other grass lineages approximately 30–40 million years ago, subsequently evolving key adaptive characteristics. These include exceptionally rapid growth, extensive lignification, and the development of distinctive hollow stems, which set it apart from typical herbaceous grasses [48]. While fossil evidence indicates the presence of bamboo-like flora as early as the late Cretaceous (around 70 million years ago), the substantial diversification into the wide array of modern bamboo species primarily occurred

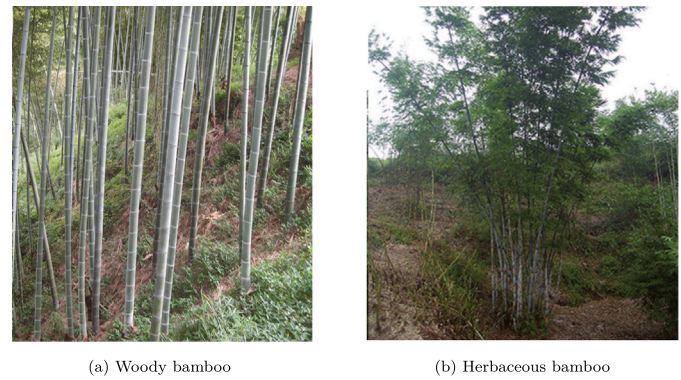


Fig. 3. Morphological diversity of bamboos: (a) woody bamboo and (b) herbaceous bamboo. After Yuan et al. [56].

during the Cenozoic era [49]. This evolutionary expansion facilitated their adaptation to a diverse range of ecological niches. Today, bamboo species form distinct communities of perennial grasses characterized by unique physiological and structural properties, and play important ecological and economic roles, particularly across Asia (24 million ha), South America (10 million ha), and Africa (2.8 million ha) [50–52].

Morphologically, woody bamboos are mainly characterized by the presence of specialized culm leaves that offer protection and support to emerging shoots, complex patterns of vegetative branching, and an outer ligule (contraligule) on their foliage leaves. They typically exhibit gregarious monocarpy, characterized by prolonged, synchronized flowering cycles that can span from a few years up to 120 years, and bear bisexual flowers [53–55]. In contrast, herbaceous bamboos generally lack differentiated culm leaves and outer ligules, display more restricted vegetative branching, usually flower nearly continuously or seasonally, and possess unisexual spikelets [54,55]. Fig. 3 illustrates the characteristic morphological distinctions between (a) woody and (b) herbaceous bamboo types.

2.2. Bamboo growth and structure

As shown in Fig. 4(a), bamboo shoots and culms develop from a dense underground network comprising roots and rhizome systems [57]. These rhizomes are broadly classified into two main types: monopodial (running) and sympodial (clumping) [58]. Monopodial rhizomes exhibit vigorous horizontal growth, often spreading rapidly. Buds on these rhizomes can develop either upwards to form a culm or horizontally to extend the rhizome network. Monopodial bamboos, commonly found in temperate climates and including genera like *Phyllostachys* and *Pleioblastus*, typically produce open stands with widely spaced culms and can display invasive tendencies. In contrast, sympodial rhizomes are short and thick, resulting in culms that emerge closely together, forming a compact clump that expands evenly outward. These bamboos are characteristic of tropical regions and are generally considered non-invasive. The prominent genus in this category is *Bambusa* [59].

A key biological difference between bamboo and many woody dicotyledonous trees is the absence of secondary xylem production [48]. This means that once an individual culm undergoes its initial rapid growth to reach the species-specific height, its diameter does not increase further over time. Furthermore, bamboo lacks the ability to regenerate xylem tissue if damaged by hydraulic stress, effectively limiting the functional lifespan of a culm to approximately a decade [60]. Consequently, a single genetic bamboo individual must continuously produce new culms to sustain its growth cycle and repeatedly reach mature height. This limitation on secondary xylem formation may reduce bamboo's competitive ability for light and water resources compared with other woody species.

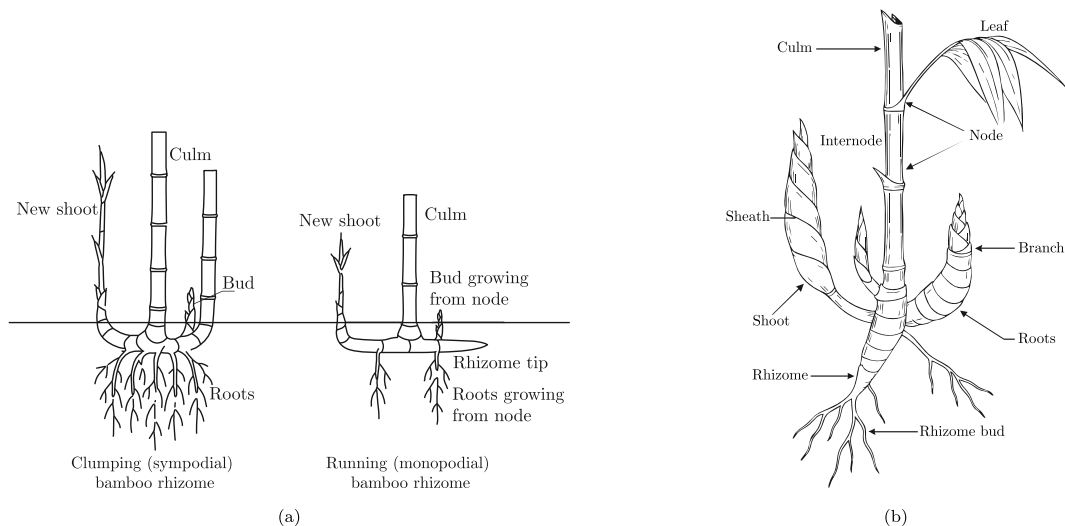


Fig. 4. (a) Structure of bamboo culm and rhizome system: clumping (sympodial) and running (monopodial) rhizomes. (b) Sketch illustrating the anatomy of a bamboo plant, adapted from Roslan et al. [57].

As illustrated in Fig. 4(b), the macroscopic anatomy of a bamboo plant can be categorized into an underground part, consisting of rhizomes, roots, and buds, and an above-ground part, composed of stems (culms), branches, and leaves [57,61]. While some bamboo species exhibit sporadic flowering triggered by environmental cues rather than strict genetic programming (e.g., *Phyllostachys elegans* in the U.S. and *Phyllostachys edulis* (Moso) in China), their flowering events are often infrequent. Table 2 provides a summary of the key structural components of bamboo and their respective functions, highlighting their interconnected roles in supporting the steady growth and vitality of the plant [62].

2.3. Cellular structure

The internal cellular structure of bamboo is markedly more heterogeneous than that of wood [63]. At the mesoscale, bamboo can be regarded as a multi-cellular biological composite with a hierarchical and functionally graded architecture [64–66]. As shown in Fig. 5, the culm wall is composed of vascular bundles embedded within a matrix of parenchyma cells [67,68]. Each vascular bundle consists of conducting elements (xylem, phloem) surrounded by a sheath of load-bearing sclerenchyma fibers [63,67].

A key feature of this architecture is the pronounced radial gradient in bundle distribution and density. The volume fraction of vascular bundles increases toward the outer culm wall, and the bundles themselves become more fiber-rich and less vessel-dominated [63,67]. A similar, though more gradual, increase is observed along the culm height [67,69]. Together with the relatively hard, waxy epidermis [70], this results in a distinct radial density gradient, with denser tissue near the exterior. This gradient is directly reflected in the mechanical response of the culm: static bending strength and modulus of elasticity (MOE) typically increase from the inner toward the outer wall [71,72]. The combination of a compliant parenchyma matrix and stiff fiber sheaths around vascular bundles thus determines bamboo’s high specific stiffness and strength and is a central target for both grading and engineered product design.

2.4. Nodes

The nodes in the bamboo culm have a notable effect on its physical and mechanical properties [73–76]. Liu et al. [73] examined the microstructure of bamboo nodes in detail using microscopic analysis of continuous sections. This work showed how the node affects the path

Table 2
Structural components and functions of bamboo. Adapted from Chaowana [62].

Structure	Function and key characteristics
Rhizome	A horizontal, segmented stem that extends underground from the parent plant, enabling vegetative propagation and colonization of new areas. It is covered with a protective sheath that safeguards emerging shoots as they develop into culms. The rhizome plays a vital role in water and nutrient storage and facilitates transport through its parenchyma and vascular tissues. It produces new shoots or culms from its nodes, enabling vegetative reproduction.
Culm	A cylindrical, woody stem consisting of nodes and internodes; typically hollow, although some species feature solid culms. Initially encased in a protective sheath, the culm provides structural support for leaves, flowers, and the branching system. It reaches full height within one growing season but attains maturity and maximum rigidity after 3 to 4 years.
Root	Roots are primarily responsible for anchoring the culms, providing stability against environmental forces such as wind and rain. They enhance the culm’s ability to support additional biomass, promoting further leaf growth and plant expansion. Roots also function in nutrient storage and typically emerge from rhizome nodes, usually extending no deeper than one foot into the soil. Bamboo roots usually exhibit a symmetrical structure in size and shape.
Branches	Most bamboo species develop multiple branches from a single bud located at each culm node. Some genera, such as <i>Chusquea</i> , can produce multiple buds per node, leading to denser branching patterns.
Leaves	Bamboo leaves are found on rhizomes, culms, and branches, comprising a blade, sheath, and ligule. Initially, leaves exist as sheaths that protect the growing rhizome underground. Upon emergence above ground, the blade develops into the primary structure for photosynthesis, converting sunlight into energy essential for growth; its shape and size vary among species. Leaf morphology is an important characteristic for taxonomic identification of bamboo species.

of fracture cracks. Fig. 6(a) presents a μ CT 3D reconstruction of the arrangement of vascular bundles in a bamboo node. The node contains two main types of vascular bundles: longitudinal and transverse [74,76,77].

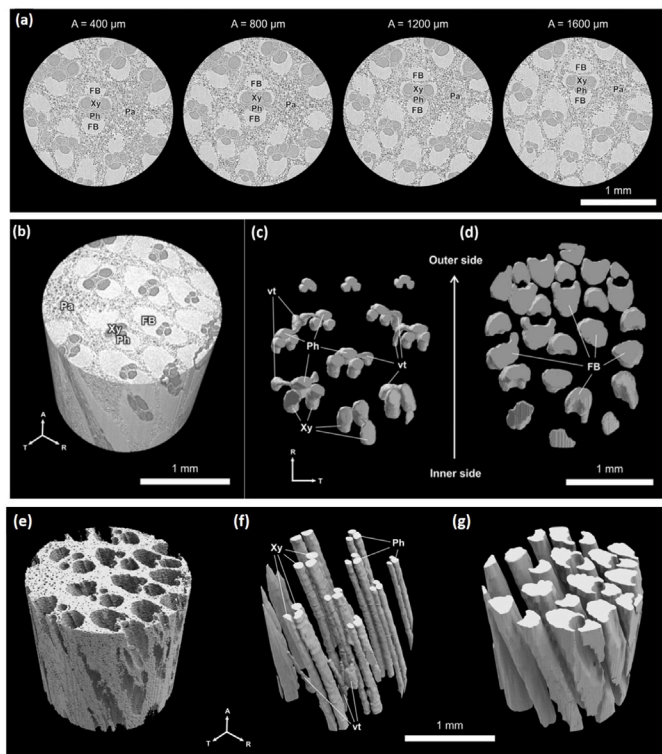


Fig. 5. μ CT 3D reconstruction of the bamboo culm wall: (a) cross-sections and anatomical details; (b) full 3D reconstruction; (c) axial view of segmented phloem, vascular traces, and xylem; (d) fiber bundles (sclerenchyma); (e)–(g) segmented parenchyma, conducting elements, and sclerenchyma (Ph = phloem, Xy = xylem, FB = fiber bundles, Pa = parenchyma, vt = vascular traces; a = axial, T = tangential, R = radial). After Palombini et al. [68].

The longitudinal vascular bundles in the node are usually thicker and larger in volume than those in the internode. For the transverse vascular bundles, the ones in the central part of the node are thick and long, while those on the sides are thin and short.

When a fracture crack moves toward the node, it first encounters the short and thin radial vascular bundles [73]. The crack then shifts into the interface between these bundles and the surrounding tissue. This shift initiates interfacial cracks and leads to the pull-out of the short vascular bundles, as shown in Fig. 6(b). The crack path changes and moves toward the side where fibers are pulled out. As the crack reaches the longer and thicker radial vascular bundles, similar interfacial cracking occurs. Because these longer bundles pass through the node, the cracks spread radially and traverse the node, ultimately causing failure at the node. The presence of both types of radial vascular bundles transforms a Mode I fracture in the internode into a mixed-mode fracture in the node [73,75]. This transformation increases energy absorption during fracture compared to the internode, due to additional damage mechanisms such as crack deflection, fiber bridging, and bundle pull-out [75]. These effects illustrate the reinforcing role of nodes in the inter-laminar RL Mode I fracture properties of bamboo.

2.5. Molecular structure

On the cell-wall scale, bamboo is primarily composed of cellulose, hemicelluloses, lignin, and a smaller fraction of ash and extractives [78,79]. These constituents form an integrated polymer network in which cellulose microfibrils provide tensile stiffness, hemicelluloses act as a flexible matrix linking microfibrils, lignin imparts rigidity and compressive strength, and extractives contribute to color and natural durability. Table 3 summarizes typical variations in the cellulose,

hemicellulose, and lignin content across the culm wall of Moso bamboo, illustrating that the chemical composition and thus the potential performance vary between the inner, middle and outer regions [70,80].

Cellulose consists of very long chains of D-glucose linked by β -glycosidic bonds that aggregate via hydrogen bonding into microfibrils [81]. Hemicelluloses are a family of heteropolysaccharides (e.g., xylans and mixed-linkage β -glucans; Fig. 7) that occupy the space between microfibrils and help control wall flexibility and moisture interactions [82,83]. Their composition and structure evolve with the culm age and radial position within the culm wall, leading to spatial differences in the hygroscopic behavior and dimensional stability [84–88]. Lignin, distributed mainly in the middle lamellae and specific wall layers, reduces permeability and provides resistance against compression and biological attack, while low-level extractives (phenolics, resins, fatty acids, etc.) further enhance natural durability [89].

The layered ultrastructure of the cell wall further reinforces this anisotropic performance. As illustrated in Fig. 8, bamboo fiber walls comprise a thin primary wall and a multi-layered secondary wall with alternating thick and thin lamellae [80]. Thick lamellae predominantly contain aligned microfibrils along the fiber axis, while thin lamellae exhibit more transverse orientations and higher lignin content [91–94]. Together with the highly lignified middle lamella, this polylamellate architecture provides high axial stiffness and strength, controlled transverse compliance, and enhanced fracture resistance compared to more homogeneous wood fibers [80,95].

2.6. Research questions at the plant scale

- How can the inherent natural variability in bamboo properties (e.g., between species, age, height position, and radial position) be effectively characterized, predicted, and standardized to ensure reliable performance in structural and engineered bamboo products for energy-related infrastructure or sustainable materials applications? [67,69,71,85,96]
- How do the molecular composition and cell wall ultrastructure of bamboo contribute to its mechanical behavior, and what opportunities exist for chemical or physical modifications to enhance properties such as strength, durability, and dimensional stability? [78,80,91]
- How can the complex hierarchical and gradient cellular structure of bamboo, particularly the role of nodes and vascular bundles, be further understood and potentially biomimicked or engineered to optimize material performance, fracture resistance, and energy absorption for advanced applications? [63,68,73,75,76]

3. Bamboo forests: foundation of a sustainable value chain

As discussed in Section 1, bamboo holds substantial potential for widespread adoption as a construction material. The value chain for bamboo as a construction material starts with the cultivation and harvesting of bamboo forests. Globally, bamboo resources span over 36 million hectares of forest and non-forest areas, accounting for approximately 3.2% of the total forest area in the reporting countries [34]. Crucially, the expansion of bamboo construction does not inherently raise deforestation concerns; rather, sustainable management practices can drive net resource growth. This is substantiated by the case of China [97], where dedicated efforts focusing on bamboo plantation establishment and management have resulted in significant resource expansion, with an estimated 30% increase in monopodial bamboo forests [97]. The productivity of intensively managed *Phyllostachys edulis* forests in China is particularly notable, demonstrating impressive annual yields of 7–10 tons per hectare, which surpass the yields of many naturally grown softwood (e.g., Norwegian spruce) and hardwood (e.g., American red oak) forests [61].

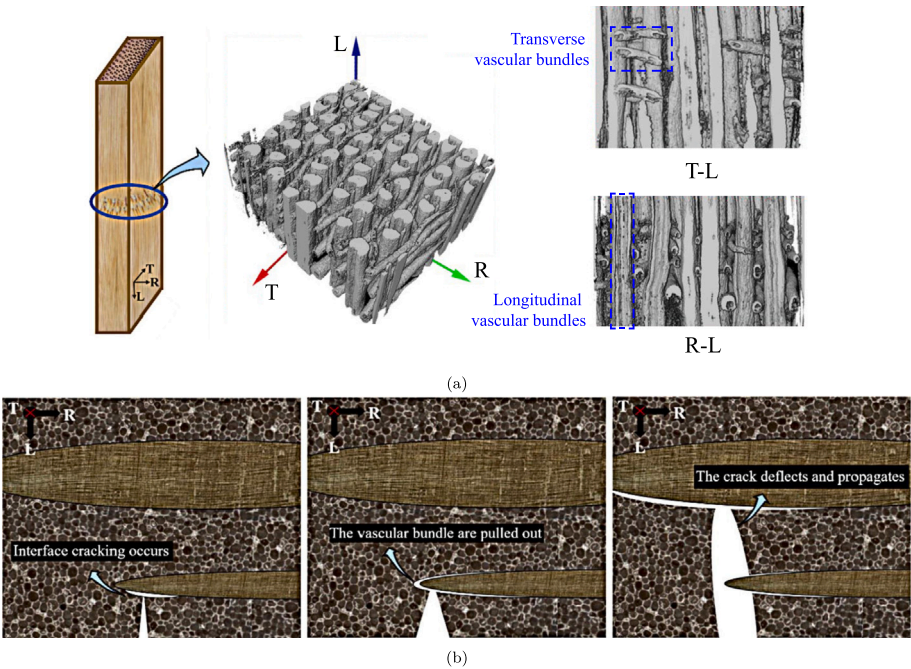


Fig. 6. (a) μ CT 3D reconstruction of the distribution of vascular bundles in a bamboo node. Adapted from Chen et al. [77]. (b) Illustration of crack deviation and fiber pull-out near a bamboo node. After Liu et al. [73].

Table 3
Data on chemical composition across the culm wall (middle section) of Moso bamboo. Data from Nkeuwa et al. [80] and Jiang [70].

Chemical composition	Outer layer	Middle layer	Inner layer
Cellulose (%)	67.67	68.38	63.02
Hemicelluloses (%)	22.40	27.15	24.01
Lignin (%)	27.90	24.01	23.68

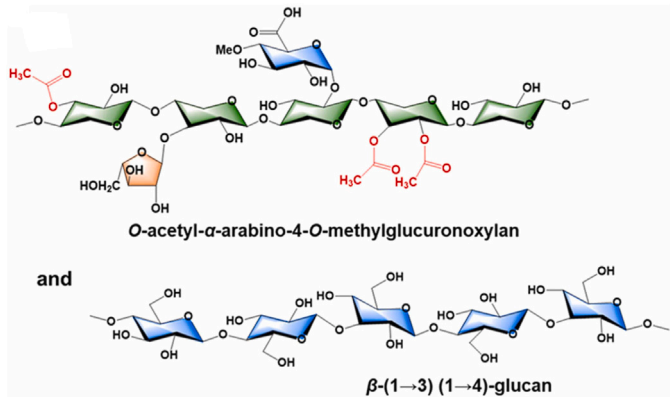


Fig. 7. Structural formulas of hemicelluloses from bamboo fibers and parenchyma cells (*O*-acetyl- α -arabino-4-*O*-methylglucurono- β - (1 $\rightarrow$ 4)-D-xylan and β - (1 $\rightarrow$ 3)(1 $\rightarrow$ 4)-glucan). Adapted from Bai et al. [90].

3.1. Global distribution patterns and resource characterization

Understanding the global distribution of bamboo species is essential for characterizing the overall resource base available for sustainable value chains. While naturally widespread, the current patterns have been significantly influenced by human introduction efforts, propagation techniques, and selective breeding based on desired traits [59, 98–100]. Historical activities, particularly extensive cultivation in Asia,

have facilitated the widespread movement and establishment of certain woody bamboo species globally.

This practice has created a selection bias, with Asian genera like *Bambusa* and *Phyllostachys* dominating global introductions. *Phyllostachys* species, largely originating from China, have a high rate of introduction outside their native range, with several species classified as invasive [101–103]. While regions like South and Central America possess rich native bamboo diversity (e.g., 429 woody species, about 39% of woody bamboo species worldwide), their exploitation has historically been limited compared to Asia, primarily focusing on local use [104]. Consequently, bamboo transfers within the Americas have largely occurred at a regional scale, and the broader potential of these native species remains largely underexploited [105].

Patterns of introduction reflect broader trends in plant translocations, with a bias toward species chosen for human uses, especially in horticulture. This preference can elevate invasion risk because such species are often exotic and tolerant of environmental stress [106–109]. As a result, prospective introductions must be rigorously assessed, particularly for taxa that exhibit weedy behavior in their native ranges, including *Pleiblastus argenteostriatus*, *Fargesia nitida*, *Sasa chartacea* (East Asia), *Ochlandra travancorica*, *Melocanna baccifera* (India), and *Guadua tagoara*, *Guadua paraguayana*, *Guadua angustifolia* (South America) [110–117]. Such precautionary evaluation is essential to mitigate ecological impacts associated with the expansion of the bamboo resource base.

3.1.1. Mapping and characterizing global bamboo forest resources

Accurately mapping global bamboo forest resources is fundamental for sustainable management and supply chain planning [118]. Bamboo forests are widely distributed, primarily located in tropical and sub-tropical regions (Fig. 9), with significant concentrations in Southeast Asia, parts of Africa, the Amazon rainforest, and the fringes of the Andes [52,119–121]. Among all continents, Asia dominates global bamboo production, contributing 56.9% of the world’s resources (Fig. 10a). Key countries with the largest reported bamboo forest resources include Brazil, China and India [52], which account for 23.4%, 20.6%, and 18.3% of global resources, respectively, underscoring their role as major resource hubs [52].

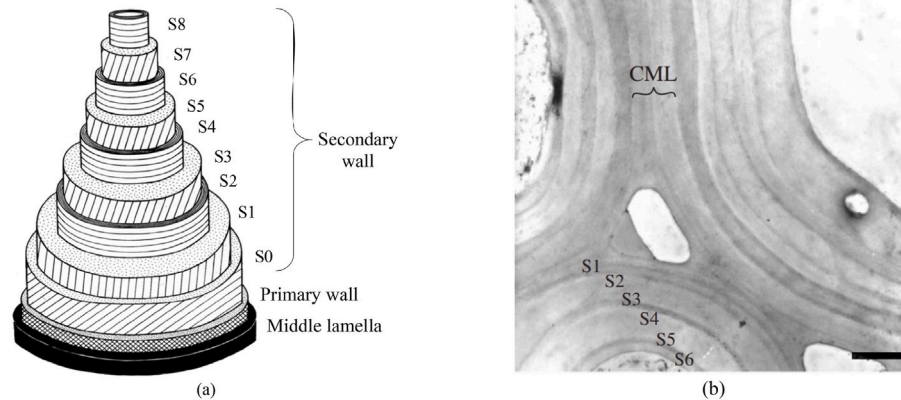


Fig. 8. Ultrastructure of bamboo cell wall: (a) schematic model of the polylamellate fiber-wall structure and (b) TEM cross-section of Moso bamboo fiber cell walls. Adapted from Nkeuwa et al. [80].

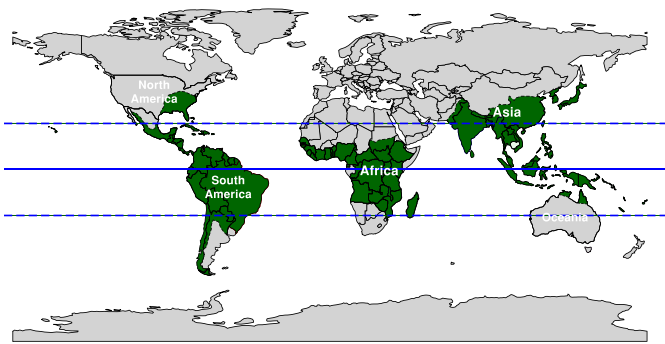


Fig. 9. Original distribution of bamboo in the world. Adapted from [120,121].

Historically, mapping has been challenging due to the significant overlap in spectral reflectance signatures—the unique patterns of light reflection across various wavelengths—between bamboo and other vegetation types, which complicates their differentiation. However, recent advancements leverage satellite data and machine learning for improved detection accuracy [122,123]. Early global mapping studies, including one based on MODIS and Landsat 8 OLI observations, estimated the total bamboo extent at approximately 30.5 million hectares using a decision tree approach [52]. Remote sensing now plays a critical role, with continuous advances in the exploitation of optical and SAR datasets [122],

and Sentinel-2 time-series imagery has been shown to be particularly effective for identifying highland bamboo forests [123].

Despite advancements, challenges remain in accurate mapping. A major hurdle is the spectral variability caused by phenomena like “on-year” and “off-year” growth cycles and shadowed areas [124]. The distinct color differences between these stands are shown in Fig. 11, illustrating one such challenge. Indices like the Normalized Shadow Vegetation Index (NSVI) have been applied to classify these areas, revealing differences in photosynthetic efficiency and carbon sequestration potential [125,126]. Although shadowed areas receive less light, they may compensate with increased chlorophyll content, contributing to higher sequestration efficiency [127,128].

Other environmental conditions influencing mapping include insect outbreaks, which modify spectral signatures [129], and dense over-story trees in tropical ecosystems, which can mask bamboo in remote sensing imagery [130]. Despite these challenges, remote sensing has enabled bamboo mapping to extend beyond traditional strongholds such as Asia to new regions in South America and Africa [131]. Enhanced data acquisition and mapping methodologies are essential for accurately characterizing its global range, tracking changes in its extent, and fully harnessing its potential within sustainable supply chains [118].

3.2. Environmental benefits: land use efficiency, carbon sequestration, water, and soil

Unlike steel, concrete, brick, timber, cement, sand, and aggregates—which depend on extracting finite resources—bamboo can be cultivated

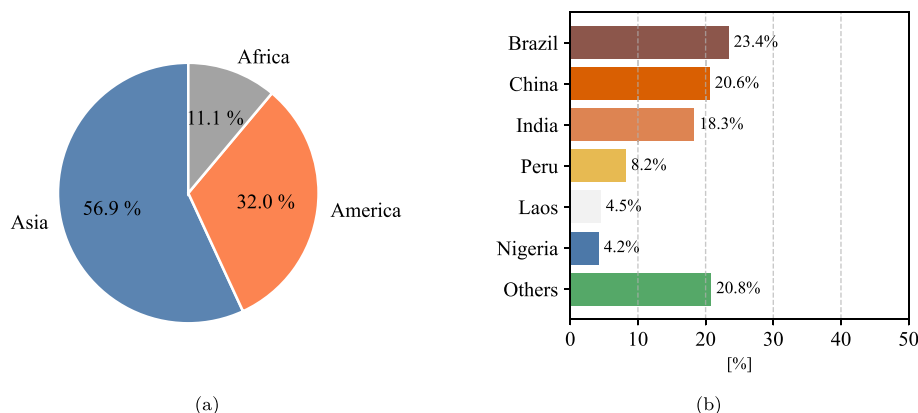


Fig. 10. Distribution of bamboo resources by (a) continent and (b) countries. Data from Du et al. [52].

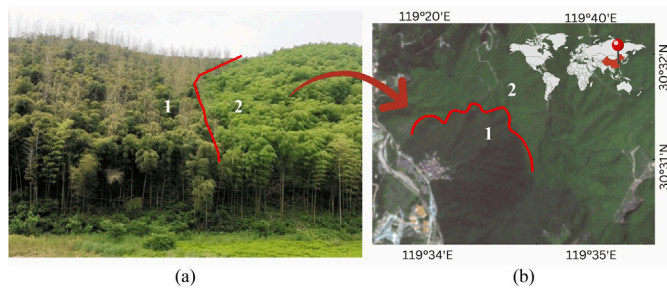


Fig. 11. (a) Photos and (b) true color composites of Sentinel-2 data of on-year (darker green, number 1) and off-year (lighter green, number 2) spatial phenomena taken on May 04, 2018, Zhejiang Province, China. Adapted from Li et al. [124].

renewably and deliver wide-ranging environmental benefits: substantial carbon sequestration, oxygen production, soil erosion control, soil enrichment, watershed regulation, biodiversity conservation, and landscape enhancement. The following subsections examine the benefits most relevant to sustainable management—land-use efficiency, carbon sequestration, water regulation, and soil protection—in greater detail.

3.2.1. Land use efficiency

Efficient land use is a fundamental aspect of sustainability, particularly as we transition from mining and fossil fuels to renewable bio-based resources like bamboo. The concept of the Ecological Footprint highlights the growing demand for the regenerative capacity of the Earth, indicating that humanity currently consumes resources faster than they can be replenished [132,133]. In this context, renewable materials offering high productivity per unit of land area are essential.

Bamboo presents a compelling solution due to its rapid growth and ability to thrive even on degraded or non-productive land, such as eroded slopes. A defining characteristic of bamboo is its rapid growth rate and short harvesting rotation compared with conventional wood. Bamboo culms are typically mature within 3–4 years, depending on species and site conditions [134]. With well-designed rotation strategies, a productive bamboo plantation can typically sustain an efficient annual harvesting cycle [135]. In contrast, typical harvest rotations for softwood and hardwood timber forests range from approximately 35 to 70 years [136,137].

The rhizome system of bamboo allows for harvesting without destroying the root structure, facilitating rapid regeneration and contributing to high land yield compared to many other crops or wood forests [138]. Furthermore, bamboo demonstrates broad environmental adaptability, low specificity for terrain and soil while showing lower water dependency and good tolerance to drought, facilitated by its rhizome and culm water storage capacity [139]. Short rotations, together with high environmental adaptability, result in substantially greater land-use efficiency. This, in turn, establishes bamboo forests as an abundant and rapidly renewable resource and supports the favorable life cycle carbon balance of bamboo construction products discussed in Section 1.2.

3.2.2. Carbon sequestration

Bamboo's significant contribution to climate change mitigation is based on a highly efficient carbon cycle and substantiated by robust quantitative data [40,140,141]. Driven by its rapid growth, bamboo functions as a powerful net carbon sink, where the rate of photosynthetic absorption significantly surpasses the carbon released through autotrophic respiration [142]. The carbon is stored within the plant's biomass, particularly in the culms, with managed plantations achieving sequestration rates that can exceed 20 tons of CO₂ per hectare annually [143,144]. The perennial rhizome system enables continuous regeneration after harvest, sustaining this carbon capture capacity without the need for replanting.

Empirical studies underscore bamboo's substantial role as a carbon sink. For instance, the Moso bamboo forests alone, which constitute 63% of China's total bamboo area, are estimated to hold a carbon stock of approximately 538.56 Tg C over a 100-year period [145]. Comparative analysis reveals that the carbon density of Moso bamboo forests is competitive, being comparable to the average of China's broader terrestrial forest ecosystems and often exceeding that of many other plantation types (see Table 4 for a detailed comparison) [142,146]. A critical advantage for the built environment is the exceptional carbon storage potential in harvested bamboo products. Moso bamboo products lead major timber types with a carbon density of 2.39 Mg C hm⁻²a⁻¹ (potential: 3.32), significantly surpassing values from ten other plantation species (0.49–1.97) [146].

Therefore, when bamboo culms are manufactured into durable construction materials (Fig. 1), the sequestered carbon is transferred into a long-term, human-made reservoir. Within the EN 15,978 framework, this biological uptake and the initial transformation of bamboo into construction products are primarily associated with the product stage (Modules A1–A3). The carbon remains stored during the building use phase, while the ultimate net climate benefit depends on the end-of-life pathway: it may be released through disposal and treatment processes in Modules C1–C4, or partially retained/recovered through reuse, recycling, or energy substitution benefits reported in Module D.

3.2.3. Water regulation and soil erosion control

Bamboo forests offer significant benefits beyond carbon sequestration, positioning themselves as a natural solution for integrated watershed management [147,148]. The dense fibrous network of bamboo roots and rhizomes serves as a natural binder, securing soil particles and providing essential stability to vulnerable areas, such as riverbanks, hillsides, and erosion-prone slopes [148–150]. This structural reinforcement not only prevents soil erosion caused by landslides or runoff but also facilitates long-term soil recovery by preserving the physical integrity of degraded landscapes. Bamboo's ability to thrive in such environments has made it a widely recommended and cost-effective strategy for land stabilization, especially in regions susceptible to instability [149,151,152]. By anchoring the soil and reducing displacement, bamboo fosters ecosystem restoration and supports sustainable land management practices.

Bamboo's role in water management is crucial, encompassing both hydrological regulation and water quality enhancement. During periods of heavy rainfall, bamboo's rhizomes and culms absorb and store substantial amounts of water, which is subsequently released through the transpiration process during dry spells to help alleviate drought conditions and maintain consistent river flows [143,153]. Simultaneously, the bamboo canopy intercepts rainfall, dispersing its kinetic energy and promoting water infiltration, thereby reducing soil impact and minimizing erosive runoff [154,155]. Furthermore, bamboo's dense root systems act as natural filters, trapping sediments and absorbing excess nutrients, such as nitrogen and phosphorus, and pollutants like heavy metals from agricultural or industrial runoff. This ability to mitigate eutrophication and contamination risks underscores bamboo's value in preserving water quality [149,156,157].

Beyond its contributions to soil stability and water management, bamboo significantly enhances soil fertility. Nutrient cycling within bamboo forests is highly efficient, resulting in minimal nutrient loss during harvesting. This is primarily because harvested culms have a very low mineral nutrient content [158]. A substantial portion of the nutrient-rich biomass, including leaves, branches, and the extensive root/rhizome system, remains in the forest after harvesting. The continuous decomposition of these organic materials returns substantial organic matter and nutrients to the soil [159–161]. This nutrient cycling process helps maintain both the physical structure and the chemical composition of the soil, creating a healthy environment for ongoing bamboo growth and supporting broader ecosystem functions [162].

Table 4

Carbon stored in ecosystems and products for major plantation forests in China. Data from Li et al. [146].

Ecosystem Type	Area (10 ⁴ hm ²)	C _{VEG} (Tg C)	C _{GL} (Tg C)	C _{SOIL} (Tg C)	Total C (Tg C)	Product C (Tg a ⁻¹)
Cunninghamia lanceolata	853.86	290.63	41.82	985.47	1317.91	16.86
Populus	757.23	167.27	5.41	340.77	513.44	9.25
Pinus massoniana	335.85	77.33	11.13	262.21	350.66	4.29
Larix gmelinii	285.79	78.80	11.34	267.20	357.34	4.45
Eucalyptus	254.14	23.59	0.77	48.06	72.41	1.24
Pinus tabuliformis	148.84	26.53	3.82	89.94	120.28	1.44
Pinus echinata	122.58	22.85	3.29	77.46	103.60	1.25
Cupressus funebris	122.51	21.94	1.61	76.71	100.25	1.19
Pinus armandii	52.37	12.52	1.80	42.45	56.77	0.70
Pinus yunnanensis	44.68	11.15	1.61	37.79	50.54	0.62
Total	2977.85	732.58	82.56	2228.04	3043.18	41.30
Phyllostachys heterocycla (Moso bamboo, current)	426.75	135.96	16.37	458.83	611.15	10.19
Phyllostachys heterocycla (Moso bamboo, potential)	880.45	324.80	34.00	972.64	1331.43	29.22

Note: C_{VEG}, C_{GL}, and C_{SOIL} denote the carbon stocks in vegetation, the ground layer (including shrubs, herbs, and litter), and soil, respectively. “Total C” denotes the total ecosystem carbon stock, calculated as C_{VEG} + C_{GL} + C_{SOIL}. “Product C” denotes the annual amount of carbon transferred from harvested forest biomass into products. “Tg C” denotes teragrams of carbon, “hm²” denotes hectares, and “a” denotes year.

3.3. Challenges and drawbacks in bamboo utilization

While bamboo offers significant potential for sustainable development due to its rapid growth, environmental benefits, and versatility, its widespread utilization and commercialization remain underdevelopment globally [163]. Despite numerous studies highlighting bamboo's benefits, fewer critically examine the practical challenges hindering its broader adoption in sustainable supply chains [164–168]. Key obstacles include limited market access, geographical limitations affecting transport, insufficient technical expertise for processing and application, and inconsistencies or shortages in the supply of quality raw material. Some of these overarching challenges, such as market access, raw material consistency, and sustainability issues, are summarized in Fig. 12.

The harvested material itself is susceptible to biological degradation from pests and fungi, necessitating effective preservation treatments to ensure long-term durability, especially in construction applications [169]. Variability in culm quality, influenced by species, age, and cultivation practices, presents challenges for standardization, which is crucial for reliable use in construction [170].

Industrial-scale bamboo production can also present ecological challenges. Although bamboo's rapid growth, vegetative propagation, and low-input cultivation contribute to its value as a renewable biomass resource, these same traits may create ecological risks when species are introduced outside their native ranges or cultivated without adequate management [171]. In such contexts, aggressive spread may alter understory structure, suppress local vegetation, and create a barrier to acceptance from both ecological and regulatory perspectives. Even within native regions, disturbance and fragmentation can favor local bamboo expansion and increase competitive pressure on other plant communities [111,113]. For this reason, the sustainability of bamboo deployment should be evaluated not only in terms of productivity and carbon benefits, but also in terms of regional ecological suitability, species selection, and containment/management strategies. At the same time, when appropriate native species are used under controlled conditions, bamboo can provide important ecological co-benefits, including land stabilization and restoration of severely degraded sites [172,173].

Furthermore, bamboo faces significant market competition from entrenched conventional materials, and shifting consumer and industry perceptions requires sustained effort. Price fluctuations, influenced by disruptions and inconsistent supply of quality raw materials, introduce uncertainty for stakeholders [164,174]. Effectively addressing these issues through robust supply chain management, spanning cultivation, processing, and distribution, is essential for scaling up bamboo utilization sustainably [175].



Fig. 12. Main challenges and drawbacks related to bamboo exploitation.

3.4. Research questions for bamboo forests

- How can sustainable harvesting practices for different bamboo species and regions be optimized to maximize yield while ensuring long-term ecosystem health and biodiversity conservation? [134,142,176]
- How can supply chain logistics for bamboo be improved to enhance efficiency, reduce costs, and minimize the environmental footprint from forest to construction site, particularly for large-scale applications? [34,177,178]
- What are the most effective methods for developing and implementing robust certification and traceability schemes that verify the sustainable and responsible sourcing of bamboo for global markets? [34]
- How do different bamboo forest management practices impact soil health, water quality and availability, and carbon sequestration potential, and what are the optimal practices for maximizing these environmental benefits? [34,139,144–146,179,180]
- What are the socio-economic implications of expanding bamboo cultivation and industry, particularly for local communities in major bamboo-growing regions, including aspects like job creation, land tenure, and community livelihoods? [34,178]
- How can technological advancements in bamboo processing (e.g., preservation, engineered bamboo products) enhance its durability, structural performance, and applicability in diverse construction scenarios while minimizing energy and chemical inputs? [34]

- What is the full potential of bamboo forests and bamboo-based products to contribute to national and global climate change mitigation targets, considering both carbon sequestration in forests and long-term storage in built structures? [143–146,179,180]

4. Processing and treatment of bamboo for engineering applications

Bamboo, though less geometrically and dimensionally regular than timber, offers significant advantages for engineering applications. It is cost-effective, abundant, available in useful sizes, and readily processed into engineered products that optimize its inherent structural properties. These processed materials exhibit enhanced dimensional stability, durability and predictable performance, positioning them as sustainable alternatives to traditional materials with mechanical properties comparable to timber [23,181]. A thorough discussion of harvesting regimes and pretreatment protocols is essential, as these foundational steps determine the raw material's suitability for subsequent industrial manufacturing.

4.1. Harvesting

Bamboo harvesting plays a crucial role in maintaining the productivity and ecological stability of bamboo forests and plantations. As a perennial woody grass, bamboo produces new shoots constantly, with culms reaching maturity within three to five years and naturally senescing after about five to eight years [182]. Selective harvesting of mature culms is essential to sustain clump vigor, prevent overcrowding, and enhance both material quality and stand health. Retaining younger culms ensures a balanced age gradient that supports continuous regeneration and long-term yield stability [183].

To ensure bamboo's environmental advantages, sustainable harvesting practices are essential. This typically involves selectively cutting only a portion of culms annually (e.g., 20–25%), which allows for the continuous emergence of new shoots and maintains a stable, productive stand [176,183]. Mature culms are typically cut at the first internode, approximately 10–15 cm above the ground, using a sharp instrument and a 45° inclined cut to ensure a clean surface that prevents water accumulation and unwanted sprouting [183]. At least six culms older than one year should be retained per clump to sustain photosynthetic function and nutrient transfer. The optimal harvesting cycle is not fixed but varies based on species, local conditions, and factors such as economic considerations (transportation, harvesting costs), technical feasibility, environmental impacts (e.g., soil erosion, water conservation), and the intended application of the harvested bamboo. For most clumping species, a cutting cycle of two to three years has been found effective in balancing culm yield and natural regeneration capacity [182,183].

Because mature culms in clumping species are often located in the inner core of the cluster, specific harvesting layouts have been developed to improve accessibility and minimize disturbance. The horse-shoe method opens a U-shaped passage from the periphery toward the center on the side with fewer young culms, while the tunnel (X-shape) method involves intersecting paths (approximately 60 cm wide) that provide entry from multiple sides to reach the central culms [184,185]. Comparative field experiments on *Dendrocalamus hamiltonii* and *Gigantochloa scorteichinii* have shown that such open-type techniques promote higher shoot emergence and easier access for harvesting compared with random or clear cutting [184,185]. Similarly, a five-year experiment on *Oxytenanthera abyssinica* in Ethiopia demonstrated that moderate-to-high harvesting intensities (50–75% of mature culms) under the X-shape technique resulted in greater shoot sprouting and thicker culms than in unharvested controls, highlighting the benefits of regulated selective felling for sustainable productivity [186].

Harvest timing is also a critical factor influencing post-harvest performance and forest health. Culm extraction should ideally be conducted

in the early dry season, immediately after the rainy period, when starch and moisture contents are at their lowest, thereby reducing susceptibility to biological vectors [182]. Harvesting during the shoot-emergence period must be strictly avoided to prevent damage to rhizomes and developing buds. Empirical observations across Asia and Africa confirm that maintaining moderate harvesting intensity, periodic rotation, and an inverted J-shaped age structure supports both ecological resilience and sustainable bamboo yield [183,187,188].

After harvesting, proper handling and field management are essential to preserve culm quality and maintain site productivity. Cut culms should be promptly transported to collection points to prevent staining and fungal infection; in small-scale operations, they are often manually carried or skidded along prepared trails, while large-scale plantations may employ animal traction or light vehicles for bundling and transport [183]. Remaining residues (e.g., branches, leaves, and damaged culm fragments) should be removed or evenly distributed as mulch to maintain soil moisture and nutrient cycling. Periodic cleaning of clump interiors improves aeration, reduces fire risk, and facilitates future shoot emergence, ensuring that post-harvest management forms an integral part of the sustainable bamboo production cycle.

4.2. Initial processing and grading

Following harvesting, culms are transported to processing facilities for primary preparation in a manner comparable to timber sawing. The culms are cleaned, nodes and surface defects are removed, and they are cut to the required size.

A significant challenge for the structural use of bamboo culms is their inherent variability in mechanical properties, which can differ even within the same species [189]. This variability arises from a range of factors at both macroscopic and microscopic scales, including species, age, moisture content, culm height, radial position within the wall, and the presence of nodes [190–193,356]. To ensure structural reliability, each culm intended for a load-bearing application, whether used directly as round bamboo or processed into an engineered product, must be strength-graded according to established standards such as ISO 19,624 [194]. These standards provide engineers with the characteristic strength values needed for design, corresponding to specified strength classes [195–197]. These criteria may include dimensional, visual, geometric, mechanical, and physical properties, which are assessed through non-destructive observations and measurements. To complement these methods, machine learning techniques are now being explored to enhance the accuracy and reliability of predicting bamboo's compressive strength [198–200].

As illustrated in Fig. 13(a), the grading process recommended in ISO 19,624 [194] may involve visual assessment, machine-based evaluation, or a combination of both, with any culms failing to meet the minimum requirements being rejected. Visual grading is defined as the process of classifying bamboo culms according to observable characteristics that influence their mechanical or structural capacity. The sorting criteria for visual grading are based on two categories of indicators: condition properties, such as surface defects or damage, and geometric properties, such as external taper ($\alpha_e = (D_b - D_t)/L$), internal taper ($\alpha_i = [(D_b - D_t) - 2 \cdot (\delta_b - \delta_t)]/L$), and bow ($b_o = b_{\max}/L$), as shown in Fig. 13(b). Machine grading refers to the classification of bamboo culms based on grade-determining properties such as strength or stiffness [201–203]. These key properties can be directly measured, inferred from indicating properties, or assessed non-destructively during grading. The selection of these properties is guided by their relevance to structural design, and characteristic values are generally derived from experimental data in compliance with ISO 22,156 [195] or ISO 12122-1 [204].

4.3. Treatments

Due to its primary growth pattern, bamboo does not develop natural protective layers, such as bark or heartwood, that are common in trees with secondary growth. This leaves the culm vulnerable to attack

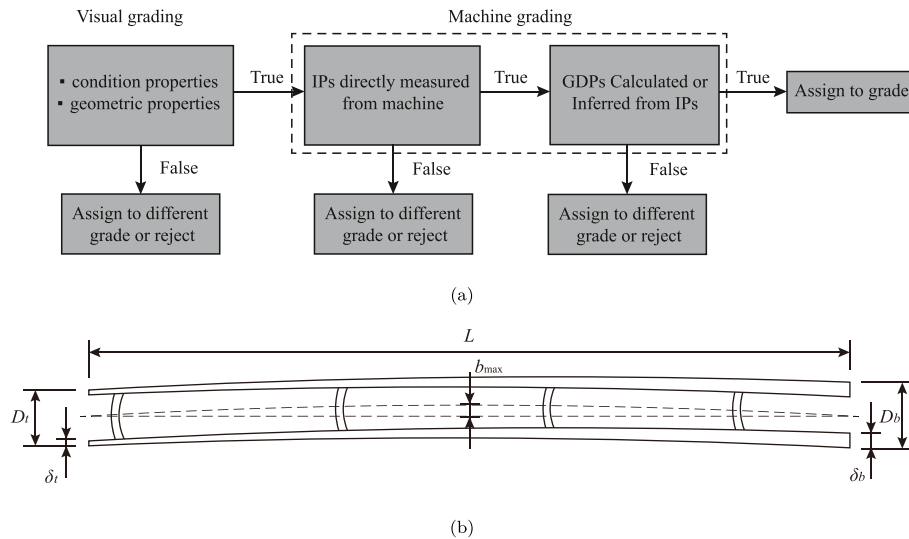


Fig. 13. (a) Hybrid grading process and (b) common geometric properties for bamboo culms. Adapted from ISO 19,624 [194].

by fungi, insects, and other biological agents, especially when moisture and nutrients like starch are present [94,205,259]. Furthermore, direct exposure to natural weathering, involving wetting-drying and freeze-thaw cycles, leads to degradation of chemical components like lignin and hemicellulose, impacting microstructure and reducing mechanical properties over time [206–209]. Additionally, solar ultraviolet (UV) radiation induces photo-oxidative degradation of the surface lignin, manifested as discoloration and surface micro-cracking which exposes the underlying fibers to further deterioration [210–212]. Such degradation compromises the structural integrity and dimensional stability of the material, rendering untreated bamboo unsuitable for long-term construction applications.

Preservation and modification treatments are therefore essential to limit biological and environmental damage, improve durability, and enable long-term use in construction. These treatments are generally the first major step after harvesting and initial processing. They prepare the material for subsequent stages, such as drying, shaping, or assembly into engineered products, ensuring consistent performance in structural applications. Broadly, bamboo treatment strategies focus on several key approaches: reducing water ingress through hydrophobic treatments or filling internal voids [213]; impregnating active agents like biocides or fire retardants [214]; and applying surface coatings as physical barriers against environmental factors [215]. These strategies are typically achieved through physical or chemical processes such as impregnating the material, applying surface coatings, or modification treatments that fundamentally alter the chemical composition and structure of the bamboo cell wall itself. These modification methods change the material's inherent nature to enhance stability, durability, and can also influence mechanical properties.

Specific methods for enhancing bamboo durability and stability are discussed in the following subsections, including modification methods and barrier/filling treatments. However, it should be noted in advance of the discussion that these treatments should not be regarded as environmentally neutral interventions. Depending on the route adopted, they may introduce additional chemical burdens, leaching risks, or process-energy demands, and their sustainability must therefore be evaluated in relation to the service-life extension they provide [39,169]. In practice, treatment selection should be based not only on immediate improvements in durability and dimensional stability, but also on whether the initial burden is offset by reduced maintenance and replacement over the intended exposure period [216].

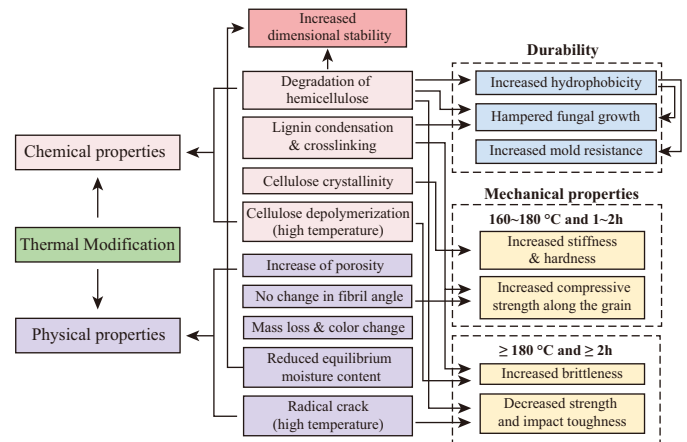


Fig. 14. Property changes involved in thermal modification.

4.3.1. Modification methods

Modification treatments represent a fundamental approach to up-grading bamboo's material performance by actively altering the chemical composition or molecular structure of the cell wall polymers [217, 218]. Unlike passive preservation methods that merely impregnate void spaces or apply superficial protective layers, modification aims to permanently mitigate the material's inherent limitations—specifically its high hygroscopicity and dimensional instability [219,220]. By targeting the abundant hydrophilic hydroxyl groups ($-OH$) and accessible nutrients within the hemicellulose and cellulose, these treatments seek to transform the cell wall from a hydrophilic substrate into a dimensionally stable and biologically durable matrix [221,222]. The two most prominent categories of such interventions are thermal modification and chemical modification.

Thermal modification is a widely applied and feasible technique for enhancing bamboo's dimensional stability and durability against biodegradation [222–225]. The process involves heating bamboo under controlled conditions, commonly in dry tanks with saturated vapor (e.g., 140–160 °C) or in sealed dry kilns (e.g., 180–200 °C) [222]. Heat treatment induces significant changes in both chemical composition and anatomical structure, as summarized in Fig. 14.

Table 5
Chemical component contents of bamboo during heat treatment.

Samples	Mass loss (%)	Holocellulose (%)	α -Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)
Untreated	0	67.05	41.54	25.51	22.06	6.27
Heat (180 °C)	3.22	59.43	32.42	27.01	25.67	8.25
Heat (200 °C)	7.83	53.54	26.61	26.93	31.67	9.07

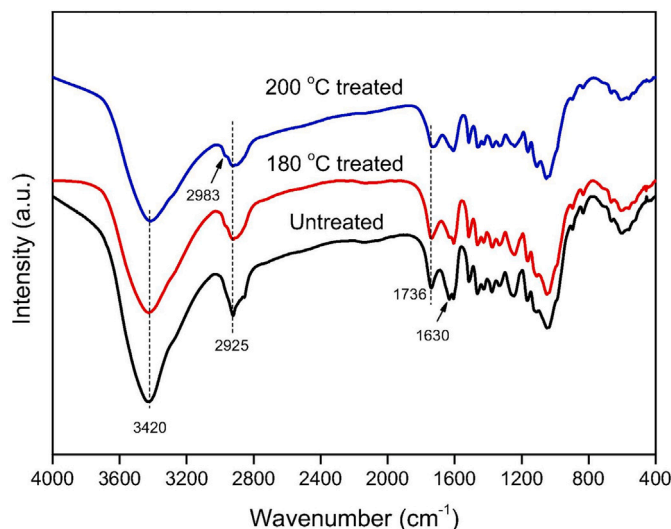


Fig. 15. FTIR spectra of bamboo samples before and after heat treatment. Adapted from Huang et al. [222].

Chemically, heat treatment modifies the relative contents and structure of the main constituents (cellulose, hemicelluloses, lignin, and extractives; see Section 2.5) as summarized in Table 5 [226]. Hydrolysis of acetyl esters in hemicellulose produces acetic acid, leading to depolymerization and dehydration under acidic conditions. This process reduces free hydroxyl groups, thereby decreasing hygroscopicity. Cellulose undergoes some degree of depolymerization, but crystallinity may slightly increase, which contributes to increased tensile strength [77,226–228]. Lignin is less reactive but can cleave at high temperatures, forming phenolic groups that increase cell wall cross-linking. These changes result in a less elastic and less hygroscopic cell wall, leading to enhanced rigidity, dimensional stability, and resistance to biodegradation [229–231]. FTIR spectra, such as those in Fig. 15, show reduced intensity of the hydroxyl stretching band after heat treatment, indicating improved hydrophobicity [222].

Thermal modification induces distinct anatomical changes, including cracking between vascular fiber cells and twist deformation of parenchymal cells, primarily attributed to differential shrinkage [232]. Parenchymal cell walls may notably delaminate, especially at temperatures above 170 °C, a phenomenon correlating with significant hemicellulose degradation, while surface properties show a significant decrease in wettability and an increase in contact angle [232]. These physical alterations necessitate a trade-off with mechanical performance, the effects of which remain underexplored and show considerable variation in the literature depending on process severity. While some studies observe negligible changes in tensile, compressive, or bending strength with only slight reductions in elastic moduli under mild conditions [233], others report substantial strength losses at treatment temperatures above 180–200 °C or with prolonged exposure, likely consequences of the aforementioned hemicellulose degradation and micro-structural damage [234,235].

Chemical modification involves the use of external chemical reagents that react with reactive groups in bamboo cell wall polymers to alter

properties, primarily reducing hygroscopicity and enhancing durability [217,220,221]. While historically effective, treatments based on heavy metals and toxic elements like chromated copper arsenate (CCA) are being replaced due to environmental concerns [236]. Promising alternatives include low-cost soluble salts, particularly boron-based compounds such as disodium octaborate tetrahydrate (DOT), boric acid, and borax [218,237–239]. Boron compounds (specifically DOT) are favored for their non-invasive nature regarding mechanical properties. For instance, Gauss et al. [221] reported that bamboo treated with 5% and 8% DOT solutions using a vacuum/pressure method not only preserved its flexural modulus but also significantly enhanced the compressive strength by approximately 30–35%, likely due to the accommodation of forces by salt crystals within the microstructure [221]. Citric acid (CA) has also emerged as a bio-based cross-linking agent [240]. When used as a binder in bamboo particleboard hot-pressed at 180–200 °C, CA markedly reduces water absorption and thickness swelling relative to binderless boards, which has been attributed to ester linkages between carboxyl groups of CA and hydroxyl groups of the bamboo particles [240,241]. These quantitative improvements underscore the transition from passive preservation to active molecular modification.

Chemical penetration into bamboo tissue is generally more challenging than into wood due to the absence of extensive radial ray cells and the refractory nature of the outer epidermis. Traditional effective preservation methods include open tank cold soaking (requiring drilling holes in internodes), modified Boucherie methods (forcing preservative axially through vessels), and vacuum-pressure treatment [242,243]. To overcome anatomical limitations, recent research has focused on energy-assisted impregnation technologies. Weng et al. [244] demonstrated that 10 min of microwave treatment can increase the porosity of bamboo slices by about 19%, thereby facilitating deeper chemical penetration. Similarly, ultrasound-assisted treatment has proven effective; studies show that ultrasound pretreatment can disrupt the structure of the cell wall and increase the permeability of the bamboo pits [245–247].

4.3.2. Barrier and filling treatments

Barrier and filling treatments differ fundamentally from cell wall modification methods. Rather than altering the chemical structure of the cell wall polymers, these treatments introduce extrinsic substances to fill internal voids or form continuous protective layers on the surface. The primary objective is to establish physical barriers against moisture ingress, biological agents, and environmental weathering. These methods are broadly categorized into two main strategies: deep impregnation, which targets the internal microstructure, and surface coating, which seals the exterior interface [248–250].

Among these strategies, impregnation treatments enhance bamboo properties by filling cell lumens and cavities with chemicals that diffuse into the internal structure. These bulking chemicals typically do not form strong chemical bonds with bamboo polymers but penetrate deeply to form a barrier, increasing density and physically blocking water uptake pathways [223,251]. Consequently, impregnated bamboo usually exhibits reduced permeability, leading to improved resistance against water and fungi, while also enhancing specific mechanical properties.

One approach involves impregnating rosin into 2,3-epoxypropyltrimethylammonium chloride (EPTAC)-modified bamboo [250]. EPTAC reacts with bamboo hydroxyl groups, while rosin impregnation improves physical and mechanical performance by creating a hydrophobic surface and filling cell voids [252,253]. Rosin's interaction

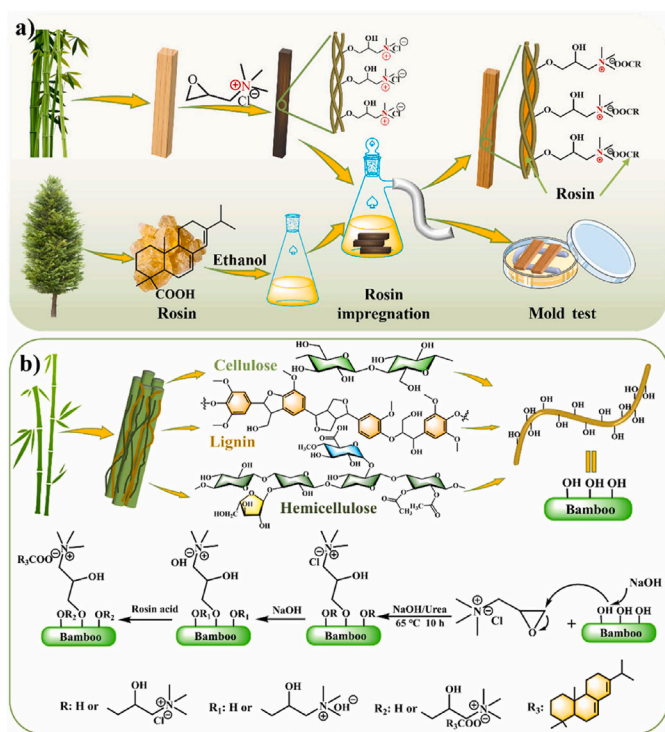


Fig. 16. (a) Impregnation procedure and (b) reaction mechanism of cationization synergistically rosin acid impregnation modified bamboo. Adapted from Chen et al. [250].

with quaternary ammonium hydroxide can form choline abietate, which contributes to mold resistance [254]. The impregnation procedure and reaction mechanism are illustrated in Fig. 16 [250]. Experimental results indicate that this synergistic treatment significantly alters the material's interaction with moisture; the initial water contact angle was reported to increase to approximately 104 ° compared to 65 ° for untreated bamboo, signifying a shift to hydrophobic behavior. Furthermore, the treatment achieved a 100% anti-mold efficiency against common fungi such as *Aspergillus niger* and *Trichoderma viride*, effectively extending the service life of the material [250].

Another prominent impregnation method uses monomers that polymerize in situ within the bamboo cells, such as furfurylation. Furfuryl alcohol, derived from bio-waste, is infused into bamboo along with a catalyst. Subsequent polymerization under high temperature forms a dense polymer network within the bamboo structure [249]. Li et al. [249] demonstrated that a weight percent gain (WPG) of approximately 10% is sufficient to confer strong biological durability, keeping the mass loss ratio below 10% against fungal decay and under 2% against termites. Furthermore, this bulk modification significantly improved hydrophobicity, reducing the equilibrium moisture content (EMC) by 34–60% compared to untreated bamboo. Liu et al. [255] further reported that surface furfurylation significantly improved the dimensional stability (ASE > 50%) while maintaining the material's original mechanical properties.

In contrast to impregnation, coating serves as a distinct surface treatment designed to apply a continuous protective layer over the bamboo substrate. This layer acts as a primary physical shield against weathering, UV radiation, and biological attack, while simultaneously enhancing the aesthetic quality of the product. Recent advancements have moved beyond simple varnishes to multifunctional hybrid coatings that significantly extend service life [256–258]. For instance, Peng et al. [256] developed a transparent, bio-based hybrid coating that achieved a high surface hardness of 9 H. Crucially, this coating endowed the

bamboo with exceptional flame retardancy (LOI of 29.1%) and mildew resistance. Wang et al. [257] utilized nature-inspired phytic acid complexes to fabricate superhydrophobic coatings. These coatings exhibited water contact angles exceeding 150 ° and sliding angles below 10 °, imparting self-cleaning properties that drastically reduce water accumulation and subsequent fungal colonization. Furthermore, innovative inorganic layers connected by “rivets” to the bamboo surface have been shown to enhance interfacial adhesion and impart robust mold-proof properties, ensuring that the protective barrier remains intact and effective even under environmental stress [258].

4.4. Drying

To meet the requirements for reliability, safety, and predictability in modern construction, appropriate drying is the critical subsequent processing step in converting treated bamboo into structural use. The primary objective of drying is to reduce the moisture content below the fiber saturation point (FSP, typically 17–25% depending on species). Achieving this threshold fundamentally suppresses fungal and insect attack, thereby enhancing biological durability [217,259]. It also improves adhesive bonding, increases dimensional stability, and enhances most mechanical properties (with the exception of tensile strength) [260–262]. Fig. 17 illustrates how various mechanical properties of bamboo change with MC, normalized by values at 12% MC. As indicated by the linear fits, shear strength exhibits the most significant sensitivity to moisture, with values near 0% MC reaching approximately 1.2 to 1.7 times those observed in green bamboo (MC > FSP). Compressive strength and MOE show more moderate increases upon drying, whereas tensile strength tends to decrease slightly as moisture content drops below the FSP. International standards such as ISO 19,624 specify that bamboo classified for structural use must have a moisture content no greater than 19% [194].

However, engineered bamboo products and round bamboo present fundamentally different drying challenges and process workflows, dictated by their distinct geometries, manufacturing routes, and energy requirements. Drying in the production of engineered bamboo is an energy-intensive process distributed across multiple manufacturing stages [265,266]. Products like glued laminated bamboo or bamboo scrimber are processed from slivers, strips, or fibers with regular geometries and large surface-area-to-volume ratios. Consequently, mechanical heating is almost exclusively employed to ensure production efficiency, such as hot-air kiln drying at controlled temperatures (typically 60–100 °C). Drying is required not only for the raw material but often repeats at various intervals, such as before treatment and prior to gluing [265]. Studies show that the multi-stage drying process accounts for a large portion of total energy use in scrimber production, with reports indicating up to approximately 47% of manufacturing energy attributed to pre- and post-impregnation drying [267]. Innovative process integrations are being investigated, such as the feasibility of a “one-time drying” strategy for bamboo scrimber [266], as well as microwave or radio-frequency drying, which offer the potential to significantly accelerate moisture removal in thicker components [268].

In contrast, the drying workflow for round bamboo is more consolidated, typically occurring before or after preservative treatment. However, the challenge lies in maintaining the full cylindrical form. Its substantial wall-thickness gradients, dense diaphragm nodes, and pronounced anisotropy in radial and tangential shrinkage generate high internal stresses during drying, making it highly susceptible to longitudinal cracking, end splitting, and internal checking [269]. Therefore, the primary goal is to lower the moisture content while minimizing defects. Drying strategies emphasize slowness and defect prevention: staged drying that combines air-seasoning with mild kiln drying is commonly adopted; opening the diaphragm nodes is a critical pretreatment to facilitate internal moisture release; and end-coating or surface impregnations are often applied to equilibrate moisture migration [270].

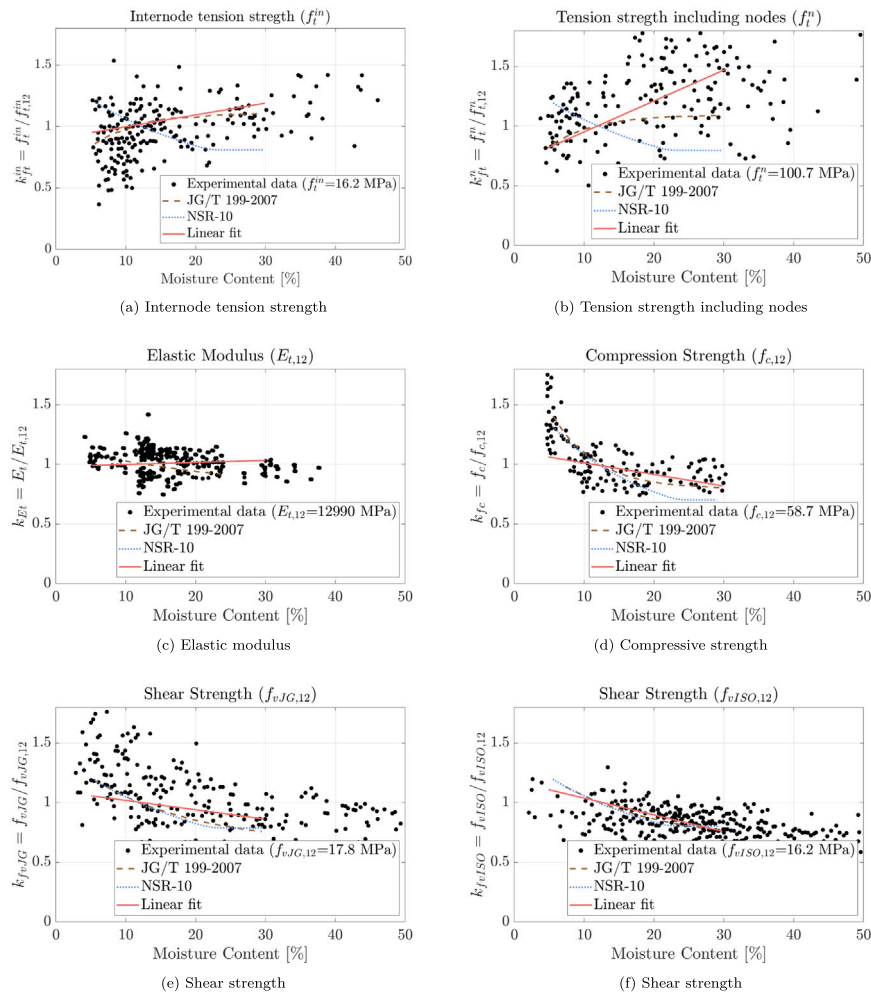


Fig. 17. Normalized mechanical properties of Moso bamboo relative to values at 12% moisture content. Data from Wang et al. [262]. Reference standards: JG/T 199-2007 [263] and NSR-10 [264].

Emerging research even explores harnessing the non-uniform stresses induced during drying to achieve controlled “3D structural reshaping” of bamboo components [18].

Beyond enabling engineered-bamboo manufacturing, drying also creates a valorization pathway for bamboo residues: offcuts and low-grade fractions can be dried and thermochemically converted into bamboo-derived biochar, which can then function as a lightweight, porous filler in insulation boards and interior lining panels. Owing to its high porosity and low effective solid-phase thermal conductivity, biochar can reduce panel thermal conductivity by increasing air-filled voids and imposing tortuous heat-transfer pathways; notably, building-envelope boards made from natural inorganic clay blended with biochars (including bamboo biochar) exhibited substantial decreases in thermal conductivity while maintaining practicable hygrothermal performance [271,272]. Comparable design principles have been demonstrated for biochar-gypsum composites, where biochar addition markedly reduced thermal conductivity (reported reductions up to ~65%) but requires careful optimization to preserve strength and cohesion [273]. Panel-scale cement- or magnesia-bonded biochar particleboards further indicate that such products can leverage biochar porosity for thermal (and potentially acoustic) damping while simultaneously storing biogenic carbon, enabling carbon-negative building components depending on feedstock, binder choice, and life cycle assumptions [274–276].

4.5. Typical bamboo-based materials for construction

In construction, bamboo is utilized in two primary forms: round (whole-culm) bamboo, the treated hollow culm harvested directly from the plant, and engineered bamboo products, which are reconstituted structural composites made from processed bamboo strips or fibers. Each category presents distinct advantages and challenges, and their suitability for specific applications depends on factors such as geometry, mechanical properties, durability, the ease of forming structural connections and cost. The following subsections examine the properties, applications, and challenges associated with both round and engineered bamboo members.

4.5.1. Round bamboo

For centuries, round bamboo has been central to vernacular architecture across Asia, Africa and South America. Round bamboo is most commonly employed directly as columns, beams, or truss members in a wide variety of structures [17,277–280]. These traditional practices reflect a deep, localized understanding of bamboo’s structural capabilities. In Southeast Asia, for example, the Filipino *nipa hut* uses bamboo poles for its primary frame (Fig. 18a) and woven mats for walls. In Latin America, vernacular techniques like *bahareque*, a wattle-and-daub system with a bamboo armature, remain prevalent, especially in seismically active regions [281,282]. Such systems underscore not only bamboo’s

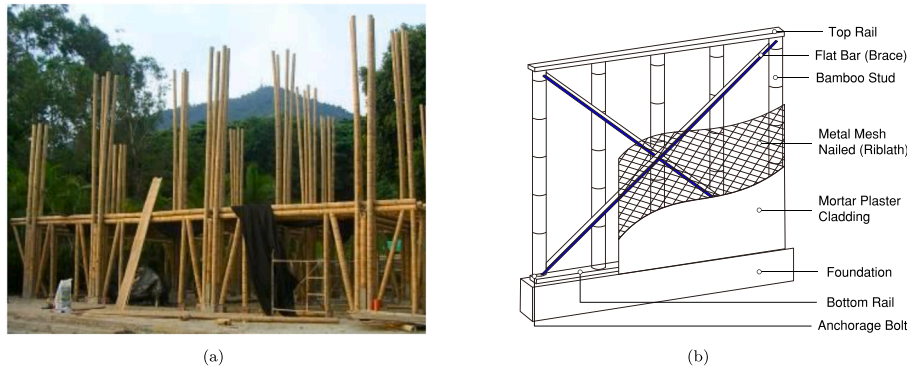


Fig. 18. Typical round bamboo member: (a) beam and column in framing system; (b) stud or brace in CBFT wall. Adapted from Archila-Santos et al. [283] and Bundi et al. [281], respectively.

mechanical efficiency but also its cultural significance and adaptability in resilient, durable construction.

To meet contemporary standards for structural safety and reliability, raw bamboo culms must undergo rigorous processes that mitigate their natural irregularity [284]. One example of this design approach combines culm grading, the use of multiple culms within each member, and capacity design principles. Together, these measures enable the construction of multi-culm bamboo members with steel connections that accommodate the natural variability of individual culms, thereby achieving more reliable and predictable structural performance [16,17]. Another example is the Cement Bamboo Frame Technology (CBFT), a modern adaptation of the traditional construction method, bahareque. In CBFT wall modules (Fig. 18b), the bamboo frame is encapsulated within a protective mortar cladding, effectively isolating the organic material from environmental stressors and biological vectors, ensuring long-term durability [285,286]. This accredited technology has been successfully implemented in over 1500 houses across areas like the Philippines and Nepal, offering a sustainable and scalable solution for affordable housing [287]. Further, digital technologies are transforming round bamboo construction by addressing the challenges posed by its irregular geometry directly in the design and construction process, demonstrating that novel bamboo architectures are feasible if these inevitable qualities are incorporated from the design conception onwards [18,288]. Advanced tools such as 3D scanning and robotics enable precise capture of round bamboo geometry and streamline mechanical testing, allowing for seamless integration into structural designs [19,289]. Parametric modeling software and augmented reality tools are also explored for real-time construction guidance, improving adaptability and precision, especially for complex geometries [20,21]. These innovations collectively enhance the efficiency, reliability, and scalability of round bamboo construction.

4.5.2. Engineered bamboo products

Round bamboo can be further processed into a range of structurally optimized materials collectively referred to as engineered bamboo. The development of engineered bamboo represents a major step in extending bamboo from a traditional natural material to a modern bio-based construction material. Through processing stages such as splitting, planing, steaming, drying, crushing, or laminating under pressure, round bamboo can be transformed into products with standardized dimensions and more reliable structural performance.

The material utilization of engineered bamboo products depends strongly on both the form of the intermediate unit and the associated processing technique. Products based on thick-walled intermediate units generally exhibit lower utilization rates and are subject to stricter requirements regarding the geometry and quality of the raw bamboo. For example, thick-strip glubam typically achieves a bamboo utilization rate of only about 30%–50%, because a substantial proportion of material is

removed during the machining of bamboo splits into accurately dimensioned rectangular strips [290]. By contrast, newer products such as arc laminated bamboo and flattened bamboo can achieve higher utilization rates, because they require only node removal together with limited removal of the inner and outer surfaces to guarantee bonding performance [80,291].

Thin-walled engineered bamboo products generally require less stringent dimensional regularization and therefore offer greater flexibility in intermediate-unit geometry and higher material utilization. In bamboo scrimber, for example, both the outer and inner layers of the culm can be incorporated into the final product, allowing utilization rates of more than 90% [292]. Similarly, radial-cutting techniques for thin strips or slices can maintain satisfactory bonding performance without removing the epidermal or waxy bamboo layer. Such approaches have already been applied in the manufacture of thin-strip glubam and oriented strand board, further improving raw-material utilization [246,293].

When material removal is unavoidable, the removed bamboo fraction need not be discarded, but can instead be reused for manufacturing secondary products or energy recovery. This highlights an important point for life cycle assessment: the environmental performance of engineered bamboo depends not only on the yield of the structural product, but also on how the residual biomass is treated within the system boundary. For example, in a recent industrial life cycle assessment of structural glued laminated bamboo, the removed bamboo fraction was modeled as feedstock for heat and power cogeneration, which substantially reduced cradle-to-gate emissions [33]. If these flows are treated as waste, the environmental advantage of engineered bamboo is weakened [37,294].

Fig. 19 summarizes the main processing pathways, showing how raw bamboo culms are converted into distinct engineered bamboo products, including glued laminated bamboo (glubam or GLB), bamboo scrimber (BS), flattened bamboo, bamboo winding composites, and bamboo-oriented strand board [295–297].

- **Glued Laminated Bamboo (glubam or GLB):** Glubam is one of the most widely used engineered bamboo products and is also commonly referred to as “laminated bamboo lumber”. Glubam is produced from planed bamboo strips (5–10 mm for thick-strip glubam, 2–4 mm for thin-strip glubam). Following pretreatment and drying, adhesive is applied to these strips, which are then arranged side by side to form laminated veneers [12]. The laminated veneers can be hot-pressed into thicker laminated bamboo boards, generally consisting of 3–5 layers with a final thickness of 10–50 mm. Xiao et al. [296] and Xiao et al. [295] further optimized this process by developing a thin-strip glubam material composed of thin bamboo strips (2–4 mm) laminated in both longitudinal and transverse directions, which provides improved cost-efficiency and a higher material utilization rate.

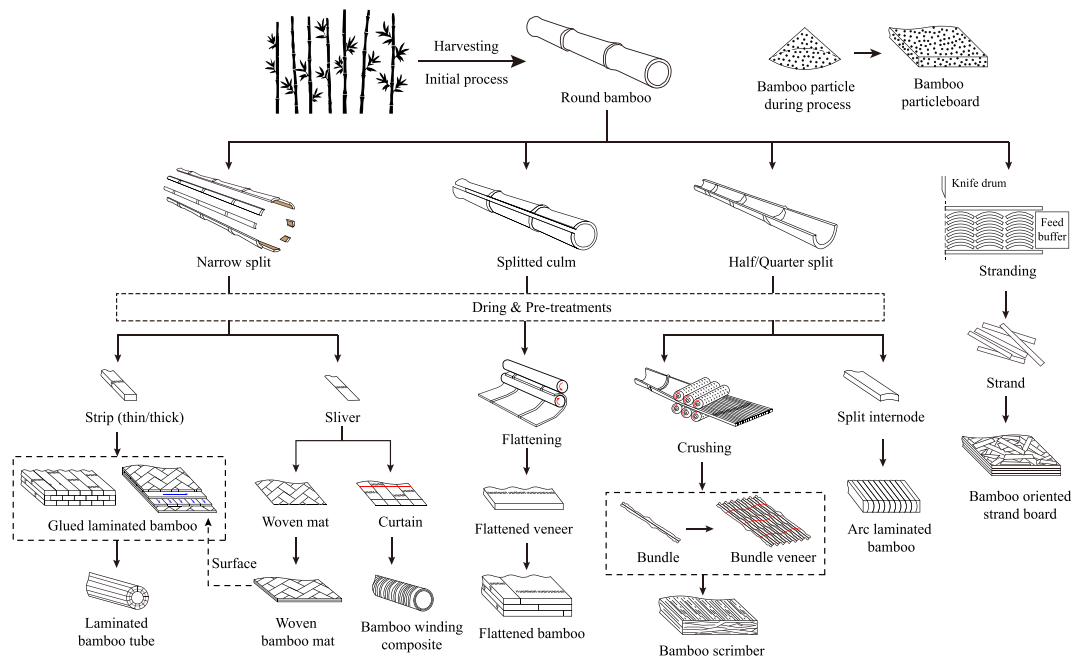


Fig. 19. Processing chain of engineered bamboo products.

- **Laminated Bamboo Tube (LBT):** The development of LBT has expanded the range of cross-sectional options available for bamboo structural members. This hollow structural form, which preserves the aesthetic qualities of natural bamboo, is derived from thick-strip glubam. In the manufacturing process, thick-strip glubam boards are machined into trapezoidal strips and subsequently hot-pressed in an annular mold to produce a tubular section. Compared with conventional rectangular cross-sections, the tubular form optimizes the distribution of material by concentrating mass away from the neutral axis, thereby increasing the moment of inertia and reducing material consumption by up to 30%. LBT demonstrates superior compressive and buckling resistance, making it a structurally efficient and sustainable solution for column applications [298].
- **Bamboo Scrimber (BS):** A high-density engineered bamboo composite manufactured by crushing half- or quarter-split bamboo culms into interconnected fiber bundles or mats, which are then resin-impregnated and hot-pressed into the final densified product known as bamboo scrimber. The resulting material typically attains a density more than twice that of natural bamboo; for this reason, it is sometimes referred to as “reconstituted bamboo” [299,300].
- **Flattened Bamboo (FB):** Created by splitting bamboo culms longitudinally, softening them with steam, flattening them into solid veneers, and subsequently laminating the veneers into boards. Since the intermediate product—flattened veneer—is directly pressed into shape, FB is generally regarded as a more environmentally friendly engineered bamboo material with reduced adhesive consumption. FB veneer is commonly used in applications such as cutting boards and tableware, whereas laminated large-section FB are primarily employed in structural engineering applications [301–303].
- **Woven Bamboo Mat (WBM):** Produced by slicing or rotary-peeling bamboo slivers from thick-walled bamboo culms or splits, which are then interlaced into woven mats and subsequently laminated in multiple layers. Rotary-peeling of bamboo culms is technically challenging and generally feasible only for certain species [23]. Alternatively, slivers can be obtained by splitting

residual bamboo from other engineered bamboo products or recovered from by-products of their manufacturing processes. WBM panels are relatively thin (typically 0.5–10 mm) and are commonly used as surface layers in laminated composites, formwork panels, and furniture components [304–306].

- **Bamboo Winding Composite Pipe (BWCP):** Fabricated from machine-stitched bamboo curtains composed of thin radial bamboo slivers bound with cotton thread, bamboo winding composite pipe (BWCP) is produced through a filament winding process. The stitched bamboo curtain is softened, impregnated with resin, and helically wound under tension onto a rotating mandrel to form a cylindrical laminate structure. Following resin curing and demolding, the pipe is cut to the desired length. As a bio-based composite, BWCP leverages the high tensile strength of bamboo fibers and controlled fiber orientation, making it suitable for lightweight structural and pipeline applications [307–309].
- **Arc Laminated Bamboo (ALB):** Manufactured from quarter-split bamboo internodes that are carefully planed and then laminated under pressure to form boards. Species with relatively long internodes are typically selected, allowing finished board lengths of up to 30–40 cm. ALB offers a comparatively high material utilization rate; however, when applied in structural components, finger-jointing is generally required to achieve greater lengths. In addition, optimization of the adhesive application process is essential to ensure the mechanical performance of this curved laminated structure [310].
- **Bamboo Particleboard (BP):** An analogue to wood particleboard, manufactured by bonding bamboo shavings, particles, or fibers with adhesive under heat and pressure. These shavings and particles can be produced by feeding culms or strips into a flaker machine, or recovered directly as by-products from other bamboo processing operations. Owing to its relatively low mechanical performance, BP is primarily used in non-structural applications such as furniture and packaging [311]. Its low density and internal void structure provide favorable thermal and acoustic insulation, making it suitable for use in interior partition panels [312].

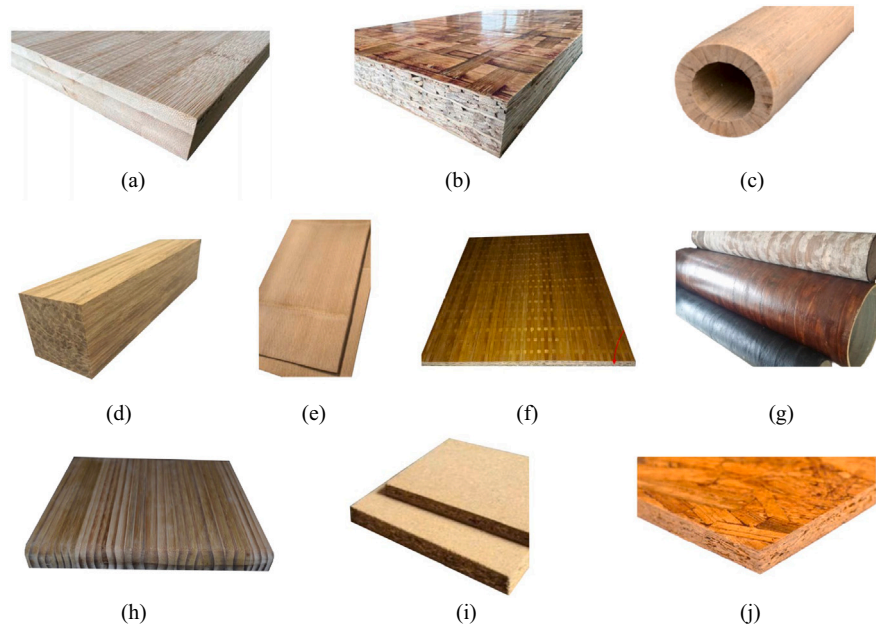


Fig. 20. Schematic of (a) thick-strip glulam [363], (b) thin-strip glulam [364], (c) LBT [298], (d) BS [365], (e) FB [366], (f) WBM [305], (g) BWCP [308], (h) ALB, (i) BP [306], and (j) BOSB [367].

- **Bamboo Oriented Strand Board (BOSB):** An advancement on particleboard technology where larger bamboo strands are aligned in specific orientations before being pressed, enhancing the panel's directional strength. The strands are typically produced from half-split bamboo culms using specialized planing machines (as shown in Fig. 19). BOSB manufacturing adapts technology from the wood-based OSB industry [313].

As illustrated in Fig. 20, engineered bamboo comprises a diverse family of products with distinct manufacturing routes and resulting structural forms, including laminated members, densified composites, hollow tubular sections, and panel products. This product diversity is directly reflected in their density levels, which are governed not only by the intrinsic characteristics of the raw bamboo but also by the degree of processing, densification, and adhesive incorporation during manufacture. At the raw-material level, the density of round bamboo is influenced by factors such as species, age, and geographic origin. Based on the dataset compiled from the literature [23,289,314–362], round bamboo (RB) exhibits an average density of 702.6 kg/m^3 with a standard deviation of 83.7 kg/m^3 , reflecting the natural variability of the material. After reconstitution into engineered products, density generally increases because the manufacturing process involves splitting the culm, rearranging the bamboo elements, applying adhesive, and, in some cases, substantial compression. Among the products examined, bamboo scrimber (BS) shows the highest average density, reaching 1104.0 kg/m^3 ($\text{SD} = 187.2 \text{ kg/m}^3$), which is consistent with its strongly densified manufacturing process. In contrast, less densified laminated products remain closer to the density range of round bamboo; for example, flattened bamboo (FB) has a mean density of 770.0 kg/m^3 ($\text{SD} = 16.3 \text{ kg/m}^3$), while glulam exhibits a mean density of 733.5 kg/m^3 ($\text{SD} = 80.5 \text{ kg/m}^3$). These results indicate that density variation across engineered bamboo products is primarily a consequence of the chosen manufacturing strategy, especially the extent of densification and the amount of added adhesive.

Different engineered bamboo products require substantially different amounts of adhesive because their manufacturing routes, densification levels, and target performances differ. Laminated products such as glulam and flattened bamboo (FB) laminates generally require relatively low adhesive input for interfacial bonding, with typical glue

spread rates of about 300 g/m^2 and 150 g/m^2 on the wide and narrow faces, respectively [316,330]. Assuming representative strip cross-sections of $10 \times 30 \text{ mm}$ for glulam and $10 \times 300 \text{ mm}$ for FB, these values correspond to estimated volumetric adhesive demands of approximately 35 kg/m^3 and 30 kg/m^3 , respectively. These products typically exhibit moderate density and mechanical performance, with reported densities generally in the range of 600 to 800 kg/m^3 [359,368]. In contrast, highly densified products such as bamboo scrimber (BS) require substantially higher resin input because the crushed fiber bundles must be impregnated and bonded into an integral composite. Reported resin contents are typically about 9 to $15 \text{ wt.}\%$ [369], which is approximately equivalent to 90 to 150 kg/m^3 of resin, and these products usually achieve superior mechanical performance with densities in the range of 800 to 1200 kg/m^3 [370,371]. For particleboard-type products, such as bamboo particleboard (BP) and bamboo oriented strand board (BOSB), the adhesive demand is usually intermediate, commonly around 8 to $13 \text{ wt.}\%$ [372,373], corresponding to about 40 to 65 kg/m^3 . These products generally have lower densities, around 500 kg/m^3 [372,373], and are therefore more suitable for non-structural applications such as interior decoration and thermal insulation.

Although considerable research has been devoted to the development of bio-based and organic adhesives [374,375], the adhesives used most extensively in industrial production still involve non-negligible environmental trade-offs. In particular, conventional adhesives are typically fossil-based and energy-intensive to produce [376], and their contribution is often reflected in an increase in the global warming potential (GWP) of the manufacturing stage (A3) [377], as discussed in Section 1.2. Higher adhesive consumption is therefore expected to increase the embodied impacts of engineered bamboo products, although the magnitude depends on product type, system boundary, and manufacturing assumptions. In practical applications, material selection should therefore not be based solely on carbon performance. Instead, it should balance low-carbon potential with the mechanical properties required to satisfy structural performance and serviceability demands.

The engineered bamboo materials described above are typically further processed through techniques such as cold pressing, finger-jointing, and other prefabrication methods to produce structural components of various sizes and cross-sections for practical engineering applications

[364]. This manufacturing and supply chain—from raw bamboo plants to structural components—can be highly standardized and exhibits a structural logic analogous to that of steel and timber construction systems [364]. In this analogy, raw bamboo culms function similarly to iron ore or logs, serving as the primary natural resource. Through standardized processing (e.g., splitting, planing, drying, and resin impregnation), bamboo is transformed into intermediate bio-based units like bamboo strips or mats, comparable to steel billets or sawn timber. These are further assembled into structural composites such as glulam (GLB), BS, or FB, functionally analogous to rolled steel sections or engineered wood products (e.g., glulam or CLT). Final stages include modular fabrication, transportation, and on-site assembly of bamboo components, following procedures comparable to those used in steel or glulam construction. The analogy underscores engineered bamboo's potential for industrial scalability and its capacity to be incorporated into global construction markets alongside conventional materials [364].

4.6. Research questions for processing and treatments

- How can the primary processing stages for bamboo—from harvesting and drying to machining—be optimized to simultaneously minimize energy consumption, reduce material waste, and enhance the final mechanical properties and dimensional stability of engineered bamboo products? [25,260,269]
- What are the most effective, scalable, and environmentally benign modification methods (e.g., advanced thermal treatments, green chemical modifications, bio-based impregnations) for durably enhancing bamboo's resistance to fire, biological degradation, and moisture, particularly for demanding exterior applications? [218, 223,249,378]
- How do thermally induced anatomical changes in bamboo culms (e.g., vascular fiber cracking, parenchymal cell wall delamination, and altered surface wettability) affect the mechanical performance, durability, and serviceability of structural components, and what processing parameters can be optimized to mitigate adverse effects while retaining the benefits of thermal modification? [232,233]
- How do manufacturing variables (e.g., adhesive type, lamination strategy, strip geometry, and the distribution of nodes) influence the multi-scale failure mechanisms, long-term creep, and fatigue performance of different engineered bamboo composites like glulam and BS? [23,96,379,380]
- How can advanced non-destructive evaluation (NDE) techniques and machine learning algorithms be integrated into industrial production lines to accurately predict the structural properties of both round bamboo and engineered bamboo, thereby reducing performance variability and facilitating robust, performance-based design? [194,197,198,201]
- What is the comprehensive life cycle environmental footprint of various engineered bamboo products when accounting for the specific energy and chemical inputs during processing and treatment, and how does this impact their overall sustainability credentials compared to conventional timber and other building materials? [133,381,382]

5. Structural use of bamboo

Throughout the 20th century, the structural utilization of bamboo was significantly constrained by prevailing public perceptions and restrictive prescriptive regulations [11]. Despite these limitations, bamboo remained a widely used construction material for scaffolding, low-rise housing, and pedestrian bridges, particularly in tropical and subtropical regions such as China, Colombia, India, and Malaysia [24,383]. Historical exploration of bamboo for structural applications includes now-critiqued concepts such as the U.S. Navy's 1960 s research into bamboo-reinforced concrete [384]. Motivated by resource scarcity, this research tested an ultimately untenable use of the material [270]. Pivotal experimental research conducted in Colombia during the late

20th century established the scientific basis for modern bamboo construction. These studies, which rigorously characterized the structural behavior of *Guadua angustifolia*, not only led to the first comprehensive national design codes but also laid the fundamental groundwork for the current ISO standards [264,385,386]. In recent decades, the emergence of engineered bamboo products (e.g., glulam, laminated bamboo lumber, and bamboo scrimber) has addressed many of the material's natural limitations. These innovations have enhanced the dimensional consistency, standardization, and chemical properties of bamboo, thereby expanding its suitability for more demanding structural applications. Moreover, the advocacy for performance-based and standardized design methodologies by numerous researchers [243,364] has paved the way for the more widespread construction of larger and taller bamboo structures. This section explores the structural systems and engineered bamboo products that support these advanced architectural applications.

5.1. Mechanical properties

Bamboo is increasingly regarded as a sustainable and structurally capable material in modern architecture. Numerous experimental studies have quantified its mechanical characteristics, laying the foundation for its broader adoption in engineering applications [23,289,314–362].

Fig. 21 presents a comparative summary of mechanical properties for round bamboo (RB) and a range of engineered bamboo products, as reported in the literature. The datasets encompass the bamboo genera most commonly employed in structural engineering due to their naturally large culm diameters—*Phyllostachys*, *Dendrocalamus*, *Bambusa*, *Guadua*, and *Gigantochloa*—with each genus including all reported subspecies (e.g., *Dendrocalamus* comprises *D. affinis*, *D. asper*, *D. giganteus*, etc.). The classification of product types follows the scheme outlined in Section 4.5.2, although only the four types most widely reported in engineering applications are considered here: glued laminated bamboo (glulam), bamboo scrimber (BS), flattened bamboo (FB), and bamboo oriented strand board (BOSB). Other engineered bamboo types described in Section 4.5.2 were excluded due to insufficient published mechanical property data.

Tensile properties of round bamboo vary notably across species (Fig. 21a and b), but broadly fall in the range of about 120–200 MPa in strength and 13–21 GPa in MOE. *Bambusa* and *Dendrocalamus* tend to occupy the upper end of this range, while *Phyllostachys* is generally lower. This spread reflects both intrinsic anatomical differences and variation in test methods and specimen preparation reported across studies.

Under compression (Fig. 21c and d), mean strengths for most genera cluster between roughly 40 and 75 MPa, with *Dendrocalamus* and *Phyllostachys* typically showing higher values. Compressive MOE values are somewhat lower than their tensile counterparts but remain in the same order of magnitude (around 12–18 GPa), again with *Guadua* and *Dendrocalamus* often at the stiffer end of the spectrum. Overall, the data confirm that round bamboo exhibits mechanical properties comparable to, or exceeding, many structural softwoods on a strength- and stiffness-per-density basis.

Shear behavior (Fig. 21e and f) is, as expected, markedly weaker than tension and compression, with shear strengths typically an order of magnitude lower than tensile strengths and shear moduli in the low-GPa range or below. Differences between genera are less pronounced than in axial properties, but *Dendrocalamus* and *Phyllostachys* generally achieve the highest shear stiffness, while some *Gigantochloa* datasets fall toward the lower bound. These results emphasize the importance of connection detailing and shear transfer mechanisms in structural design.

Flexural behavior (Fig. 21g and h) integrates both axial and shear responses. Bending strengths for most genera lie roughly between 70 and 120 MPa, with *Dendrocalamus*, *Bambusa*, and *Phyllostachys* typically performing best. Bending MOE values are broadly consistent with compressive MOE, indicating that flexural stiffness is dominated by axial properties of the outer culm wall. Taken together, the compiled datasets

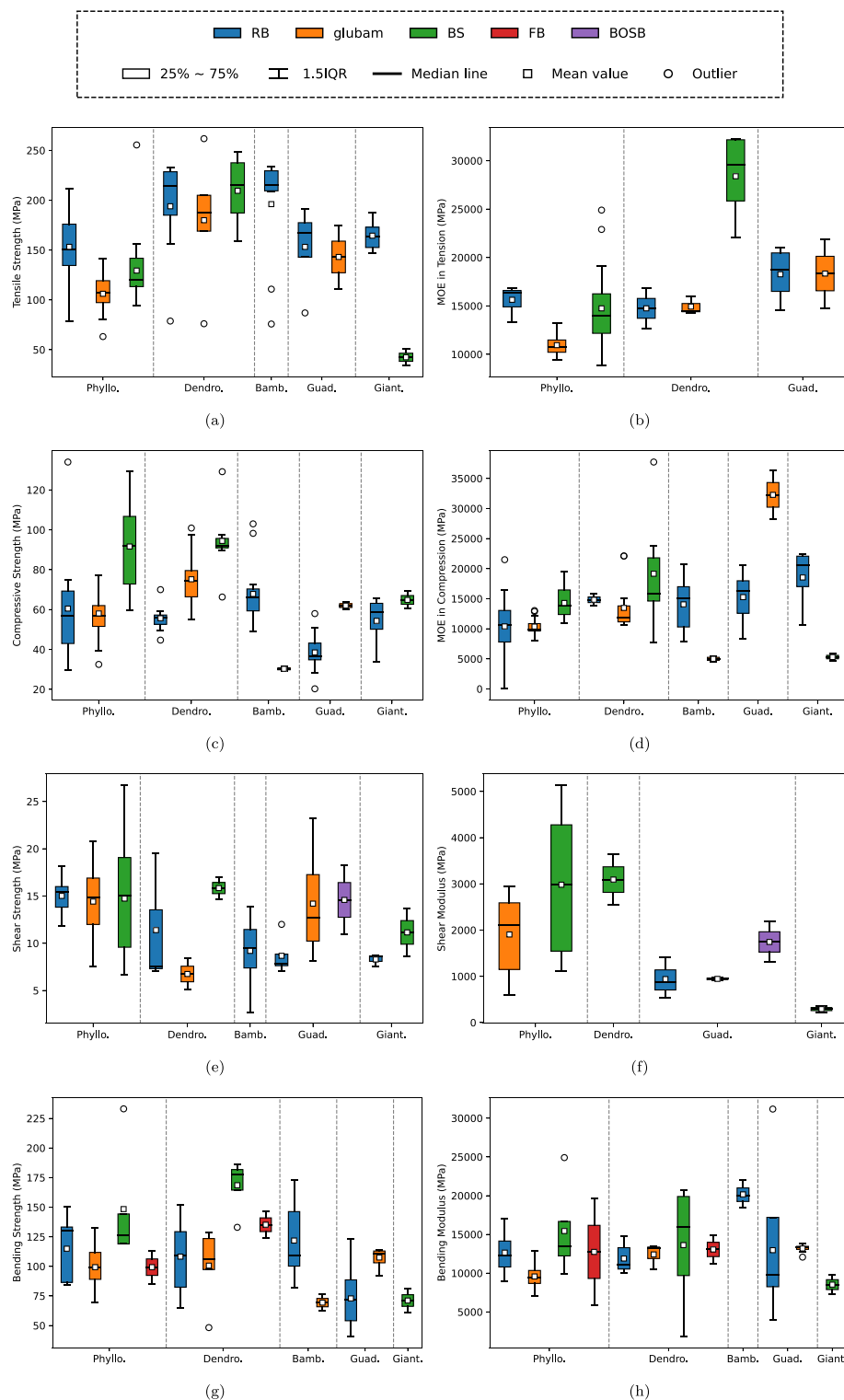


Fig. 21. Mechanical properties of round bamboo (RB) and engineered bamboo products: (a) tensile strength, (b) tensile modulus of elasticity (MOE), (c) compressive strength, (d) compressive MOE, (e) shear strength, (f) shear modulus, (g) bending strength, and (h) bending MOE. Boxplots illustrate the distribution of experimental results by bamboo species and product type, with statistical descriptors defined in the accompanying legend. Data from [23,289,314–362].

highlight both the high specific mechanical performance of bamboo and the significant inter-species and intra-species variability that must be addressed in design. Importantly, this variability does not prevent reliable structural use; instead, as with other variable construction materials, it is managed through grading, characteristic-value determination, and

calibrated safety formats. Accordingly, Fig. 21 should be interpreted as descriptive summaries of broad material populations rather than as direct design data for ungraded members.

To compare the coefficient of variation (CoV) of typical mechanical properties across different materials, Table 6 summarizes representative

Table 6
Typical coefficients of variation (CoV) for material properties.

Material	Typical Property	Coefficient of Variation	Reference/Source
Timber	Modulus of rupture	16%	USDA Forest Products Laboratory (Wood Handbook, Chapter 5, Tables 5 and 6) [387]
	Modulus of elasticity	22%	
	Compressive strength parallel to grain	18%	
	Compressive strength perpendicular to grain	28%	
Concrete	Compressive strength (> 35 MPa)	7–9% (Very good quality control) 9–11% (Good quality control) 11–14% (Fair quality control)	ACI 214R-11 (Guide to Evaluation of Strength Test Results of Concrete) [388]
Steel (structural or reinforcing bars)	Yield strength	4–6% A275 Steel 5–10% A380 Steel	Andriono and Park [389]
Masonry	Compressive strength	20–35%	Sarangapani et al. [390] Müller et al. [391]
	Modulus of elasticity	11% 20%	
Earth (earth blocks)	Compressive strength	25–53%	Raspail et al. [392]
Soil	Undrained shear strength	11–49% – Clay, Silt	Phoon and Kulhawy [393]
	Effective friction angle	10–50% – Clay, Silt	
	Undrained shear strength	6–56% – Fine grained	
	Effective friction angle	5–11% – Sand	
Round bamboo	Compressive strength parallel to grain	20–21%	Cacanando et al. [320] Correal et al. [394]
	Bending strength	20–24%	
Engineered bamboo	Compressive strength parallel to grain	6–9% (glulam)	Tang et al. [331]
		4–11% (Bamboo scrimber)	
	Tensile strength parallel to grain	10–24% (glulam)	
		13–33% (Bamboo scrimber)	

ranges reported for major structural materials. As shown in the table, round bamboo exhibits CoV values of about 20% to 21% in compressive strength parallel to grain and 20% to 24% in bending strength, which are broadly comparable to the ranges reported for structural timber, 16% to 28%, and masonry, 11% to 35%, both of which are long established in structural practice. Engineered bamboo shows a more differentiated pattern. For compressive strength parallel to grain, glulam, 6% to 9%, and bamboo scrimber, 4% to 11%, generally exhibit lower variability than round bamboo and approach the range of concrete, 7% to 14%, and even steel, 4% to 10%. For tensile strength parallel to grain, the reported CoV remains higher, particularly for bamboo scrimber, 13% to 33%, but this still falls within the broader range commonly encountered in other structural materials. Rather, round bamboo behaves similarly to other natural materials, while engineered bamboo can achieve reduced variability through manufacturing and quality control. The key engineering issue, therefore, is not whether bamboo is as uniform as steel, but how its variability can be effectively managed within a rational design framework.

To manage this inherent variability, international standards such as ISO 19624:2018 [194] provide a framework for grading bamboo culms based on visual, geometric, mechanical, and physical criteria. As discussed in Section 4.2, this grading process helps define a more uniform material population and excludes culms with defects that may adversely affect structural performance. In addition, the use of multiple parallel culms in round bamboo members can improve both structural performance and reliability compared with single-culm members [16,395,396].

Process-based control of variability is already well established in engineered timber products. Similarly, ISO 7567:2024 [397] provides guidelines on the production, strip requirements, adhesive use, pressing parameters, and quality control for glued laminated bamboo products.

Applying appropriate safety factors also reduces the uncertainty leading to a more economical design [398]. A higher CoV does not imply that safe design is impossible; it implies that the lower-tail strength lies further below the mean, so the design format must compensate by using lower characteristic values and/or larger partial safety factors to achieve the target reliability. Various methodologies address material

uncertainties, such as the characteristic value approach adopted in ISO 12,122 [204] for timber and ISO 22,156 [195] for bamboo. Recent reliability-based studies on bamboo composites and bamboo-reinforced systems confirm that design values and resistance factors can be calibrated explicitly to meet target reliability levels [320].

5.2. Connection systems

Efficient and reliable connections are critical to load transfer, overall stability, and the desired ductile behavior of bamboo structures [399, 400]. The strategies adopted vary markedly between round (whole-culm) bamboo, whose geometry and material properties are highly variable, and engineered bamboo products, whose shape and dimensions are factory-controlled. A third, rapidly growing group of solutions employs specially detailed yielding or frictional devices, often within prefabricated components, to provide seismic energy dissipation and speed up on-site assembly.

5.2.1. Connections for round bamboo

Joining hollow, tapered culms presents geometric and mechanical challenges. Fig. 22 classifies the prevailing joint archetypes into: (i) clamping joints that rely on friction along the exterior surface; (ii) through-bolt joints that transfer load by bearing stress and shear to the bamboo wall thickness; and (iii) internal-anchorage joints that transfer load by friction or shear along the inner surface or diaphragms. Because the culm wall is weak in tension and shear perpendicular to the grain, longitudinal splitting and brittle failure are recurrent concerns [401–404]. Research therefore focuses on auxiliary components (e.g., steel plates, tension bands, grout or concrete infill) that redistribute stresses and restrain crack propagation [405–407]. Round-bamboo sub-assemblies remain valuable, however, for providing lateral bracing or shear resistance within hybrid building systems, and several authors have demonstrated prefabricated shear walls that marry culm studs to glued laminated bamboo frames [278].

Recent studies aimed to improve the structural performance of the three types of aforementioned connections [409]. Traditional clamping devices (i) are not moment-resisting. Consequently, Moran and García [410] developed steel clamp joints capable of transmitting bending moments. The clamp connections exhibited higher stiffness and strength

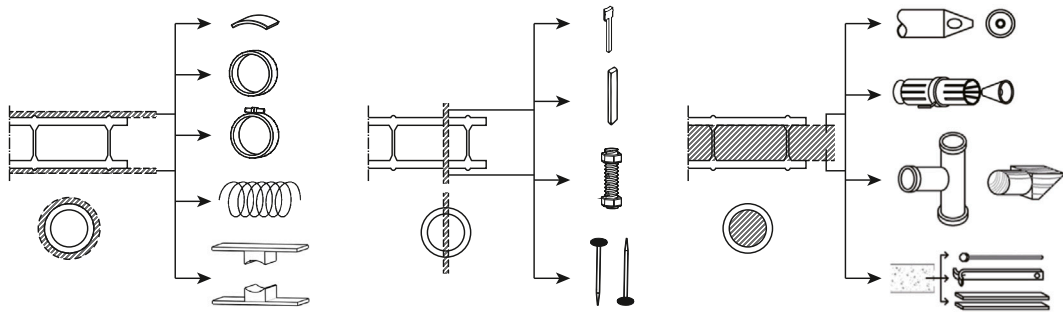


Fig. 22. Typical joint configurations for round bamboo. Adapted from Widyowijatnoko and Harries [408].

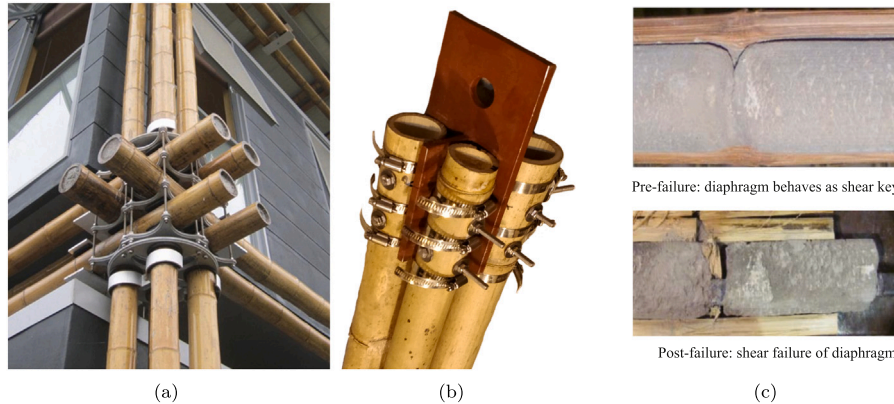


Fig. 23. Common round bamboo connections for three types. (a) Transferring force through friction on the outer surface, photo by Laverde [413], (b) compression on the wall thickness, after Pradhan and Dimitrakopoulos [16], and (c) friction on the inner surface or compression to the diaphragm, adapted from Mitch [414].

compared to traditional through-bolt joints, with one prototype (enhanced by internal mortar infill) achieving a 30%–250% increase in stiffness over bolted counterparts. Villegas et al. [279] applied steel clamping joints in a prefabricated modular truss for low-cost housing. The study found that adding two small drywall screws can improve joint redundancy and slip resistance. Masdar et al. [411] used custom-shaped wooden clamps and timber gusset plates in bamboo truss joints, as a low-cost alternative to steel clamps. Tests indicated that introducing such wooden clamp collars increased the joint's load-bearing capacity by roughly 40% compared to an unclamped bolted joint. García et al. [412] proposed ultra-thin steel semi-rings to address irregular bamboo diameters when sizing mismatch, and the need to cut the culm to exact diameters poses challenges. The BooTech construction system [413] serves as a full-scale implementation of the clamping connection concept. The system employs a characteristic clamping method to connect round bamboo, which utilizes specially designed bolts and steel connectors to fasten multiple culms together, deliberately avoiding any perforation of the bamboo to preserve its structural integrity, as shown in Fig. 23(a). It provides a versatile, low-carbon solution that accommodates bamboo poles with diameters ranging from 50 mm to 140 mm.

The second class of bolted connections (ii) introduces stress concentrations and risks of longitudinal splitting due to the bolt holes (as shown in Fig. 23b). Therefore, it is vital to provide sufficient confinement to the culm, e.g., by means of hose clamps, to drastically enhance the ultimate strength, the ductility, and the energy dissipation of bolted bamboo connections compared to unconfined culms [280,415]. Recent studies have proposed filling the hollow internodes with mortar or grout and wrapping or reinforcing the bamboo around the bolt region. Noverma et al. [416] found that a bolted connection with cement mortar infill inside the bamboo internode was significantly stronger than using a bamboo

shear pin alone. The mortar infill provides internal support to the culm wall, improving load distribution and preventing local crushing. In line with this, Correia et al. [417] developed an analytical method to predict the strength of bolted mortar-infill bamboo connections using a modified European Yield Model approach. Quintero-Dávila et al. [418] successfully applied such connections in a full-scale bamboo bridge. Researchers have also explored wrapping the outside of a bolted joint area with high-strength fibers. Awaludin and Andriani [419] wrapped vulnerable bolt regions with fiber-reinforced polymer (FRP) sheets and natural fiber rope, which delayed crack initiation. Similarly, Meng et al. [420] and others [421] successfully applied Glass-FRP wraps around bolted joints.

Regarding the third class (iii), one of the most commonly adopted configurations involves mortar-filled bamboo tubes with an embedded threaded rod (as illustrated in Fig. 23c). Load transfer in this system primarily occurs through frictional resistance between the cured mortar and the inner wall of round bamboo, in combination with the shear interlock mechanism provided by the internal diaphragm. The predominant failure mode observed in such connections is shear failure of the diaphragm, as it loses its capacity to act effectively as a shear key under increased loading. Nie et al. [422] investigated a novel bamboo-to-steel connection where steel plates are embedded inside the bamboo wall, and the hollow cavity is filled with grout. They found that bolt diameter is the main factor governing strength. To improve the structural performance under seismic loading, Zhou et al. [423] developed a steel connector for bamboo joints. The connector simply consists of a hollow steel sleeve that fits around or inside the bamboo members, creating a moment-resisting joint in a bamboo frame. A recent innovation in internal fastening is the use of double-headed screws [424], essentially steel rods with heads on both ends that anchor inside round bamboo without the need for a nut. Researchers applied these connectors in bamboo

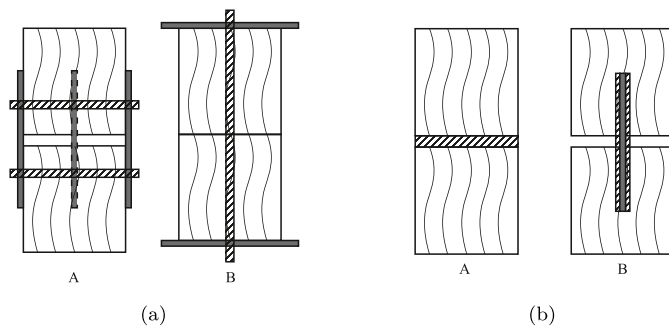


Fig. 24. Common engineered bamboo connections. Shaded areas represent load-transferring elements. (a) Mechanical fastener-based connections transfer load through shear (A) or axial (B) stress in mechanical fasteners such as bolts, dowels, or nails. (b) Adhesive-bonded connections, where load is transmitted via glue lines subjected to normal (A) or shear (B) stresses.

shear wall panels, proving them to be highly dissipative. Looking toward modern methods, some researchers have proposed prefabricated metal connector kits and even 3D-printed composite joints for bamboo. For example, Rittirong [425] prototyped a system of male/female metal pieces that snap together inside round bamboo to speed up construction. In another study, van Wassenhove et al. [426] introduced a removable 3D-printed bio-composite connection for space-frame structures.

5.2.2. Connections for engineered bamboo

Engineered bamboo products such as bamboo scrimber (BS) and glued laminated bamboo (glulam) exhibit high dimensional stability and consistent rectangular cross-sections. These properties make them compatible with connection systems traditionally used in timber construction (e.g., bolts, dowels, screws, nails, and steel plates) enabling the application of well-established Eurocode- or NDS-style design frameworks for structural evaluation [400]. As a result, connection behavior becomes more predictable, and strength classes can be explicitly addressed in design.

As shown in Fig. 24, engineered bamboo connections can generally be classified into two fundamental types: (a) mechanical fastener-based, and (b) adhesive-bonded connections. These categories reflect how load is transferred at the interface—through mechanical elements or adhesive layers—and each has distinct mechanical characteristics and typical failure modes.

Mechanical fasteners combined with steel plates represent the most commonly adopted connection method in engineered bamboo structures. Structural components of engineered bamboo can be assembled with conventional mechanical fasteners, including bolts, dowels, and nails, which are well established in timber engineering. Steel plates employed in these connections are either embedded in pre-cut grooves or mounted on the surface. The former approach is simpler and more cost-effective, whereas the latter provides a more ductile failure mode (as shown in Fig. 25a) and enhanced initial stiffness [427].

The performance of mechanical fastener-based connections depends heavily on the properties of the base material. Bamboo differs notably from timber in its mechanical response: mechanical fastener-based connections in bamboo typically fail due to shear plug formation, whereas timber tends to fail through single-split cracking [428,429]. Furthermore, the influence of nail arrangement on the performance of nailed joints exhibits opposite trends in bamboo and timber [430]. Treatment methods also significantly affect mechanical behavior; for instance, dowelled connections made with bleached bamboo exhibit approximately twice the ductility of those using caramelized bamboo [429].

To further enhance connection performance, various confinement techniques have been implemented. Wrapping the connection region

with fiber-reinforced polymers (FRP) or analogous composite materials has been shown to increase tensile capacity while reducing strength variability [431]. An alternative strategy involves the partial filling of bolt holes with adhesive, which promotes more uniform load transfer and mitigates local crushing. This method has demonstrated substantial improvements in joint capacity, with increases of up to 120% under cyclic loading conditions [432,433].

Adhesive-bonded joints (Fig. 24b) are primarily employed for lengthening engineered bamboo components or for connecting them to other materials in composite applications. The inherent porosity of bamboo facilitates effective bonding when suitable structural adhesives (e.g., phenol-resorcinol-formaldehyde or melamine-urea-formaldehyde) are used alongside appropriate surface preparation. Yeh and Lin [434] investigated the structural performance of finger-jointed laminated bamboo and found that it is influenced by factors including bamboo species, growth height, and finger joint profile. Glued-in rod connections, originally developed for timber structures, have recently been applied to engineered bamboo [435]. In this system, a threaded steel bar is embedded into pre-drilled holes in the bamboo substrate and bonded using epoxy resin. The pull-out strength of such connections is typically governed by the shear strength at the interface between the bamboo and adhesive layer, as the bond strength between bamboo and adhesive is generally lower than that between the adhesive and threaded steel bar. Liu et al. [436] introduced a resin pre-coating (RPC) method for epoxy joints between engineered bamboo and steel substrates (Fig. 25b). Their results demonstrated that the RPC treatment enhances mechanical interlocking at the interface, thereby improving fracture strength within the interfacial zone and significantly enhancing the overall bonding performance of the adhesive joint.

5.2.3. Innovative and ductile connections

For mid- and high-rise applications, connections must not only remain strong but also dissipate seismic energy. Strategies include friction-based clamps, steel sleeves that yield in bending, and glued-in rods that transfer load through controlled slip. Cross-Laminated Bamboo-Timber (CLBT) panels [437] (supported by bonding-quality and durability studies on smaller bamboo/timber laminates [438–441]) offer new possibilities for embedding such devices while maintaining planar diaphragms.

A representative solution is the semi-rigid steel-engineered-bamboo beam-column joint proposed by Huang et al. [442], in which specially detailed steel plates yield in tension and compression to dissipate energy (Fig. 26). Comparable concepts using crushable fillers or slotted-bolt friction pads are under investigation for prefabricated wall-to-foundation and truss-node connections, promising the ductility demanded by modern seismic codes.

Leng et al. [443] tested several beam-column connection configurations for bamboo scrimber frames under monotonic and reversed cyclic loading. They designed three types of joints: (1) bolted connections with outer steel side-plates (analogous to a traditional timber moment connection), (2) connections with a T-shaped steel insert that sleeves into the bamboo members, and (3) connections with double L-shaped steel angles encapsulating the bamboo end. The T-shaped steel plate connector provided superior performance: it yielded higher initial stiffness, higher moment capacity, and notably improved ductility and hysteretic energy dissipation compared to the simple side-plated joint. The dominant failure mode in these connections was cracking at the adhesive interfaces within the bamboo (i.e., between bamboo fiber bundles and resin) near the tension bolt. Beyond component tests, full-frame experiments have validated the performance of hybrid connections. Wang et al. [444] built a full-scale bamboo-steel hybrid moment frame using glulam beams/columns connected by novel ductile steel joints. The hybrid frame achieved a ductility ratio of about 1.46 and a damping (equivalent viscous) ratio of nearly 14%. As for engineered wood products, mixing bamboo

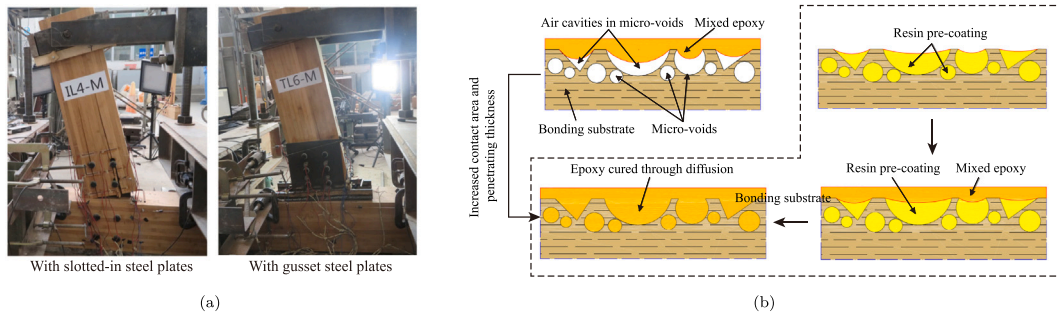


Fig. 25. (a) Observed failure modes of two types of bolted engineered bamboo connections, adapted from [Leng et al. \[427\]](#). (b) Schematic of the resin pre-coating (RPC) method used to enhance the interfacial bonding performance of adhesive joints in engineered bamboo, adapted from [Liu et al. \[436\]](#).

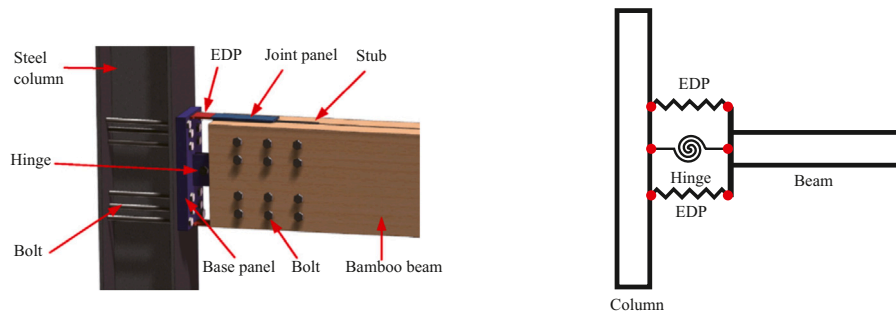


Fig. 26. Energy-dissipating steel-engineered-bamboo beam-column connection. Adapted from [Huang et al. \[442\]](#).

with steel connectors can compensate for bamboo's lack of inherent ductility.

Other researchers have looked at special joint types like rocking connections or slip-friction joints in bamboo structures to enhance seismic performance. For example, [Xiong et al. \[445\]](#) developed a moment connection with a hysteretic damper for a glulam frame. Finally, the use of alternative fasteners like glued-in rods and bamboo-based dowels is being explored to improve ductility and sustainability. [Guan et al. \[446\]](#) introduced bamboo scrimber dowels as a replacement for steel dowels in wood connections, showing comparable strength and more ductile failure, as also found in pure wood moment-resisting joints with wooden dowels.

5.3. Construction typologies

Bamboo has been used in construction for millennia, ranging from the simplest vernacular huts to highly refined contemporary structures. While historically associated with rural and tropical areas for low-rise dwellings and agricultural buildings, bamboo has also played a crucial role in urban development, particularly in Latin America, where it features prominently in the colonial architecture of many historical city centers [385]. Traditional round bamboo systems such as the bahareque walls in Latin America [447], nipa huts in Southeast Asia [448], and stilted bamboo houses in South Asia [449] are notable for their climate responsiveness, rapid construction, and use of untreated culms joined with rope, wedges, or dowels. In the 20th and 21st centuries, bamboo's role expanded into both engineered bamboo structures and round bamboo construction thanks to advancements in preservation methods, lamination technologies, and connection design [399]. Engineered bamboo products have enabled bamboo to meet the structural and safety requirements of mid-rise construction [364,437]. Bamboo construction today spans a broad spectrum of typologies, discussed in the following subsections.

5.3.1. Temporary structures

One of the most enduring traditional applications of round bamboo is in temporary structures: scaffolding. Bamboo scaffolding was widely used for the construction of low- to mid-rise buildings in South China and Southeast Asia due to its practicality and affordability [450]. It remains in use in certain regions, particularly in Hong Kong [451]. As shown in [Fig. 27\(a\)](#), this type of scaffolding can wrap entire multi-story buildings using thousands of bamboo poles secured with nylon or natural fiber straps [452]. A distinct evolution of this technique is the *Bamboo Theatre* (or *Shen Gong Xi Peng*, [Fig. 27b](#)), erected for traditional festivals.

However, this long-standing technique is now facing an unprecedented decline, driven by the intensifying demands for structural integrity and reliability in modern high-rise construction [454]. The situation was further exacerbated by a series of high-profile fires involving bamboo scaffolds [455]. While investigations confirmed that substandard management and flammable protective netting were the primary catalysts for fire spread, the inherent combustibility of bamboo remains a significant concern. A critical turning point occurred following the 2025 Tai Po fire [456], after which the Hong Kong Construction Industry Council suspended professional training and certification of bamboo scaffolding workers.

Beyond utilitarian scaffolding, bamboo is increasingly defining the aesthetic of contemporary landscape and functional architecture through temporary pavilions. A prime example is the bending-active bamboo shell structure (BABSS) shown in [Fig. 28\(a\)](#), which exploits the material's high tensile strength and natural flexibility to achieve complex, organic geometries [457]. Constructed using Augmented Reality (AR) holographic guides, this project illustrates the synthesis of traditional material properties with modern digital fabrication techniques to guide the precise assembly of complex forms. Such structures serve a dual purpose: providing functional temporary shelter while acting as sculptural landmarks that activate urban public spaces. This approach typifies the modern potential of bamboo to create immersive,

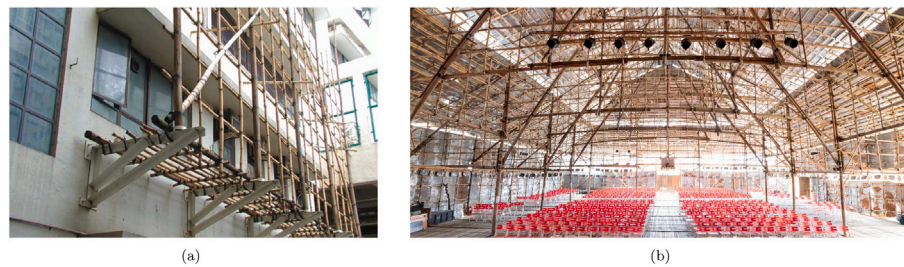


Fig. 27. (a) Steel bracket support for bamboo scaffolding. After Ramanathan [452]. (b) A bamboo theatre building in Hong Kong [453].



Fig. 28. (a) A bending-active bamboo shell structure (BABSS) serving as a temporary urban pavilion. After Jiang et al. [457]. (b) full-scale temporary sheltered pathway module prototype in the spatial configuration in the campus garden during daytime (top) and at night with LED lighting (bottom). After Wang et al. [458].

aesthetically driven environments that challenge the boundaries of conventional rigid construction.

Wang et al. [458] designed a temporary sheltered pathway using an active-bending system of bamboo strips, aiming for a lightweight, sustainable, and easily deployable structure (Fig. 28b). The final prototype features a double-arch system of bamboo strips for enhanced lateral stiffness, a substructure of laminated bamboo for flooring, a transparent PVC fabric cover, and an integrated LED lighting system. The design's performance was validated through numerical analysis and the construction of progressively refined prototypes. Fig. 28 shows the completed full-scale module, demonstrating its real-world application and aesthetic with integrated lighting.

5.3.2. Bridges

Many pedestrian bridges around the world have been constructed using round bamboo due to its availability, sustainability, and ease of use. The bamboo bridge built in 2001 (Fig. 29a) stands out as an exemplary instance of effective engineering and design using round bamboo. The bridge, situated over the Panamericana highway at the Chimayoy Natural Reserve in Nariño, Colombia, spans 20 meters with a clear width of 2.8 meters and a height of 2.4 meters [459]. Structurally, it employs a *Howe* bamboo truss system, notable for efficiently distributing loads by placing diagonal members in compression and vertical posts in tension under typical gravity loading. The bridge deck comprises a 50-mm-thick concrete slab supported by bamboo framing, providing reliable pedestrian support. The thoughtful combination of structural efficiency, joint design, and material treatment in this bridge makes it a noteworthy example of modern bamboo-based infrastructure [459].

Another noteworthy case is the round bamboo footbridge investigated by Paraskeva et al. [460] (as shown in Fig. 29b). The structure was constructed using two species of natural bamboo (*Mao Jue* and *Kao Jue*) and subjected to a series of mechanical tests in the Structural Engineering Laboratory at the Hong Kong University of Science and Technology. The 8-meter-span bridge employed a Pratt truss system, with all members composed of multiple round bamboo bundled together. To mitigate local crushing, selected nodes and components

were infilled with mortar. The structural performance was further enhanced by connecting two planar trusses with horizontal transverse members and steel wires. Experimental testing reported vertical deflection of the bridge deck under applied load and identified bamboo splitting as the dominant failure mode [460]. In a subsequent prototype, the authors improved the connection detailing to enhance structural ductility, as illustrated in Fig. 29(c). Importantly, following a hierarchical modeling of the multi-culm bamboo members and conducting a (conventional) nonlinear simulation, Pradhan et al. [17] were able to predict the experimentally observed response of the examined bamboo structure, thus verifying its predictable structural behavior.

Engineered bamboo, particularly in the form of glulam, has been successfully applied in several bridge projects, highlighting its structural viability and ecological benefits [295]. The first modern bamboo pedestrian bridge with a 5-meter span was constructed in Changsha, guided by experimental testing of prototype girder specimens [461]. The bridge incorporates hollow rectangular glulam columns—assembled from bolted twin I-shaped sections—and a cross-laminated beam system composed of three 28 mm-thick glulam plates joined by bolts, with diaphragms installed at 250 mm intervals to enhance lateral stability (as shown in Fig. 30a). In Leiyang, Hunan Province, China, a 10-meter-long single-lane roadway bridge was constructed using glulam girders (as shown in Fig. 30b). This bridge was designed to carry an 8-ton truckload and was tested with an overloaded 8.6-ton truck, demonstrating satisfactory performance with midspan deflection well within code limits [462,463].

Xiao et al. [464] presented a comprehensive evaluation of a full-scale, 9.4-meter-long CFRP-reinforced glulam bridge model, focusing on its long-term creep behavior and short-term load-bearing performance. Over a 3.7-year creep test under 10% of the ultimate bending capacity, the midspan deflection remained within acceptable limits, with no visible surface degradation observed. Short-term destructive testing confirmed that the girders retained sufficient stiffness and load-carrying capacity after prolonged exposure to creep [464].

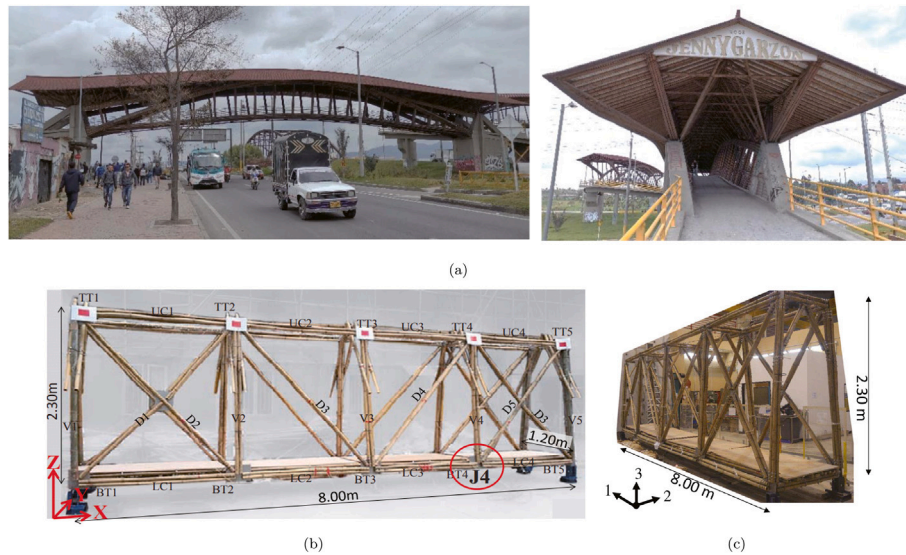


Fig. 29. Examples of round bamboo footbridges. (a) A 20-meter-span bamboo bridge in Nariño, Colombia; (b) an 8-meter-span Pratt truss bamboo footbridge constructed in Hong Kong; and (c) the improved prototype of the Hong Kong bridge. Adapted from Quintero et al. [459], Paraskeva et al. [460] and Pradhan et al. [17], respectively.

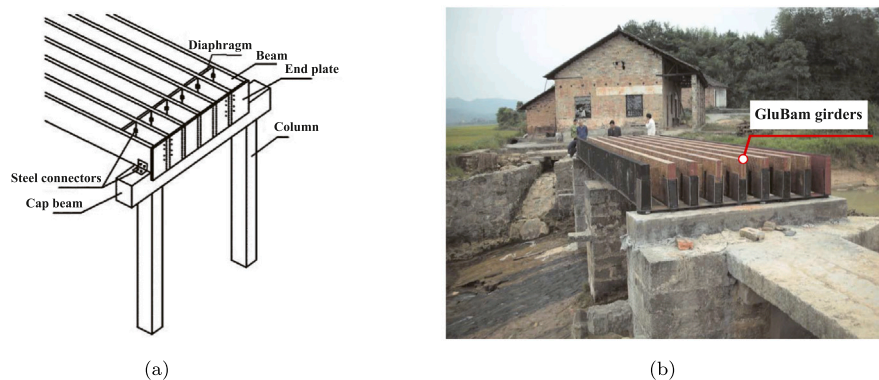


Fig. 30. Examples of engineered bamboo bridges. (a) Schematic of a 5-meter glubam bridge constructed in Changsha; (b) a 10-meter glubam bridge constructed in Leiyang. Adapted from Shan et al. [461] and Xiao et al. [462], respectively.

5.3.3. Low-rise buildings

The early exploration of bamboo as a structural material was primarily driven by the need to provide affordable and self-help housing solutions in resource-limited tropical regions, where bamboo's abundance, workability, and renewability offered a practical solution to housing shortages [243,385]. Traditional round bamboo buildings typically employ a light-frame structural system, in which beams, columns, load-bearing shear walls, roof trusses, and floor slabs are constructed from round bamboo serving as the primary load-bearing components [465]. Members are connected through lashings, pegs, or simple bolts, while infill walls consist of woven bamboo mats or wattle-and-daub panels. Representative traditional bamboo structures display diverse regional typologies, such as the wattle-and-daub bahareque houses of Colombia (Fig. 31a), stilted nipa huts in the Philippines (Fig. 31b), and thatched *kadjan* roof dwellings in Sri Lanka, all built on round bamboo frameworks with woven or plastered infill [466]. Despite their structural ingenuity, traditional bamboo houses remained limited to one or two stories due to low technical precision and material durability.

The rapid expansion of the tourism industry, together with a growing societal emphasis on environmental sustainability, has stimulated renewed interest in bamboo architecture. With advances in treatment, fabrication technologies (Section 4), and the development of innovative

joint systems (Section 5.2), round bamboo construction is being pushed toward larger, taller, and more visually expressive forms [11,467]. Designers increasingly embrace bamboo's natural curvature to achieve organic and sculptural geometries that integrate structure and space. A notable example is the Heart of School building at Green School Bali (Fig. 32a), where Jörg Stamm's structural mastery complements Ibuku Studio's design, translating round bamboo into sweeping arches and layered trusses, demonstrating how structural logic can coexist with architectural elegance [468]. With the growing professionalization of bamboo construction, design and building processes have become increasingly standardized and systematized [469]. Recent innovations have focused on enhancing connection performance and structural precision through engineered joints, prefabricated modules, and hybrid reinforcement systems. These advances enable multi-story assemblies with improved stability and load transfer. The three-story Energy-Efficient Bamboo House designed by Studio Cardenas Conscious Design (Fig. 32b) exemplifies this progress, integrating advanced joint detailing with sustainable design principles [413].

The development of engineered bamboo materials has allowed bamboo construction to overcome the structural constraints of traditional round bamboo systems, primarily associated with geometric variability and limited member size. Their improved manufacturability and



Fig. 31. Examples of (a) traditional bahareque house in Armenia, Colombia. After Kaminski et al. [466]. (b) Stilted bamboo house in the Philippines. After De Araujo et al. [448].



Fig. 32. (a) The Heart of School building at Green School Bali, Indonesia. After IBUKU [468]. (b) Energy-efficient bamboo house in Baoxi, China. After Laverde [413].

dimensional control enable standardized design, prefabricated assembly, and systematic construction. As a result, engineered bamboo products offer greater reliability and predictable mechanical performance, supporting a wider range of structural and architectural applications. Low-rise engineered bamboo structures commonly adopt structural systems analogous to those of engineered timber construction. Typical configurations include post-and-beam and braced or shear wall frames [23,364] composed of engineered bamboo members.

The lightweight glulam Frame System, developed by Xiao and co-workers, represents one of the earliest engineered bamboo structural systems designed for full-scale building applications. Experimental and analytical studies verified its satisfactory stiffness, ductility, and seismic performance, demonstrating the feasibility of glulam as a primary load-bearing material in low-rise buildings [295,364,462]. Xiao et al. [470] demonstrated the structural feasibility of using glulam in low-rise residential construction by building three two-story houses in China, shown in Fig. 33. These buildings, ranging from 120 to 255 m², employed prefabricated glulam studs, beams, and sheathing panels in a light-frame system similar to North American 2 × 4 wood construction. Indoor air quality tests and carbon footprint analyses confirmed its sustainability for housing applications [364].

The enhanced dimensional precision and manufacturing control of engineered bamboo enable its reliable application in larger and more complex commercial building structures, meeting the performance and safety requirements of modern construction. For example, a three-story office building completed in 2020 in Ganzhou, China (Fig. 34a), employs a beam-column system constructed from laminated bamboo, also known as thick-strip glulam. The building reaches a height of 12,800 mm with a total floor area of 1100 m² [472,473]. Its construction process was fully standardized in accordance with Chinese design codes, and upon completion, the building's appearance is nearly indistinguishable from that of a conventional mass timber structure. A hybrid structural system combining engineered bamboo with conventional materials such as steel and concrete represents another promising pathway toward low-carbon and

sustainable construction. The Bamboo Cubic project in Shaowu, China, features a 16.86 m-high hybrid steel-bamboo frame system, in which most bamboo components are prefabricated curved glulam members [474]. The bamboo elements and adjacent steel frames are interconnected through bolted joints with gusset steel plates, ensuring reliable load transfer and structural continuity. The completed structure satisfies both architectural and structural performance requirements while showcasing the distinctive aesthetics and reduced embodied carbon achieved through engineered bamboo.

The current development of bamboo structures focuses on integrating advanced design and fabrication technologies to achieve the highest attainable architectural standards, while simultaneously addressing environmental quality, energy efficiency, and economic feasibility. The Y-Team's award-winning Y-Project (Fig. 34b) demonstrates a successful implementation of this concept. This project is a single-story solar-powered residence in which the primary structural frame and interior finishes are extensively constructed from engineered bamboo, combined with other locally sourced biomass materials to create a climate-responsive and energy-efficient building. Engineered bamboo plays a central role in reducing the project's carbon footprint, demonstrating its potential contribution to future carbon-neutral building goals [475].

5.3.4. Mid- to high-rise buildings

Engineered bamboo possesses mechanical properties comparable to, and in some aspects exceeding, those of engineered timber, while overcoming the geometric limitations and variability inherent to round bamboo. Consequently, it holds strong potential for application in mid- to high-rise buildings of four stories or more, similar to the development trajectory of modern timber structures. With numerous successful examples of six-story or even taller mass timber buildings serving as references, engineers have begun exploring the feasibility of constructing mid- to high-rise structures using engineered bamboo materials [329]. However, as with other combustible bio-based structural materials, its use in taller buildings is conditioned by fire-safety requirements, code limitations on combustible construction, and the availability of

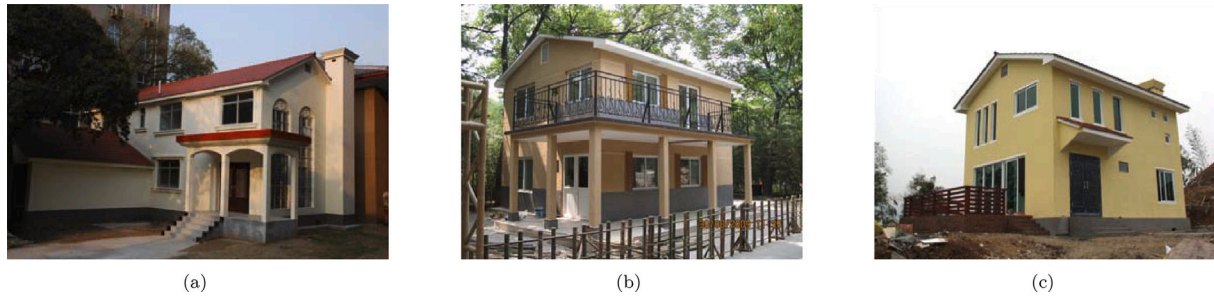


Fig. 33. (a) 255 m² house completed in February 2009; (b) 150 m² tea house built in Black bamboo Park in Beijing in August 2009; (c) 120 m² mountain house in Cailun Forest, Leiyang, Hunan Province, completed in November 2009. Adapted from Xiao [471].



Fig. 34. (a) Building of Sentai bamboo research Center, GanZhou, China. After Su et al. [472]. (b) Y-Project building presented at the Solar Decathlon China (SDC) 2022 in Zhangjiakou, China. After Han [475].

appropriate design pathways, often including performance-based fire engineering rather than reliance on prescriptive rules alone [476]. Fire resistance is discussed in Section 7.1.

Another key technical barrier to the broader use of bamboo in mid- to high-rise construction lies in the performance and reliability of structural connections. Bamboo, while exhibiting excellent compressive and tensile strength along the grain, has inherently low tensile capacity perpendicular to the grain due to its unidirectional fiber structure. Conventional mechanical fasteners often require drilling through the material, which disrupts the fiber alignment and leads to brittle cracking or splitting near the holes, particularly under tension or shear loads [329]. This failure mode undermines structural safety and limits the scalability of bamboo in demanding applications such as multi-story frames and modular systems.

One promising solution is the development of cross-laminated bamboo-timber (CLBT) panels, which strategically combine laminated bamboo in the outer layers to capitalize on its superior compressive and bending strength, with a timber core that offers reliable screw-holding capacity [437,477]. By redistributing load paths and enhancing fastener engagement, CLBT systems address the weakness of bamboo in transverse loading while maintaining ease of fabrication. One of the special advantages of CLBT is that the bamboo surface layer can be used as bamboo flooring itself, combining the interior and structural construction in one step. Additionally, ductile connection strategies (discussed in Section 5.2) are essential to enable code-compliant, structurally robust, and economically viable bamboo-based mid- to high-rise buildings.

Another critical challenge in advancing bamboo-based mid- to high-rise construction is improving lateral resistance and energy dissipation under dynamic loads such as wind and earthquakes. Although engineered bamboo products can be fabricated in large, structurally efficient sections, the anisotropic nature of bamboo and the limited development of robust strategies for lateral force resistance present significant design challenges [181]. To address this, several structural strategies have been explored. Braced frame systems provide effective lateral stiffness

with minimal material use [478,479], while shear wall systems—particularly those employing glulam or CLBT—offer improved in-plane shear strength and stiffness [437,477,480,481]. Inspired by innovations in timber structures, self-centering rocking wall systems have been proposed to enhance seismic resilience by enabling controlled rocking behavior and reducing residual deformation after strong shaking [482,483].

In terms of energy dissipation, a promising strategy is to concentrate inelastic deformation within connections or specially designed damping components, rather than in the bamboo members themselves. As discussed in Section 5.2.3, solutions such as slotted bolted joints, frictional connectors, or yielding steel elements can dissipate energy while preserving the integrity of the primary structural system. This not only prevents brittle failure typical of bamboo in perpendicular tension or shear but also facilitates post-event repair by allowing damaged connectors to be replaced.

As shown in Fig. 35, a representative example of recent advancements in mid- to high-rise bamboo construction is the Ninghai Bamboo Tower, a seven-story demonstration and research building developed at Zhejiang University-Ninghai Joint Research Center for Bio-Based Materials and Carbon Neutral Development [484], which is also the tallest engineered bamboo building to date. The tower is 20.3 m tall, with a footprint of 129 m² and a total floor area of 790 m². The primary load-bearing elements, including beams and columns, are fabricated from thick- and thin-strip composite glulam, with a longitudinal-to-transverse fiber ratio of approximately 6:1 [484]. This hybrid configuration enhances mechanical properties in both axial and transverse directions, particularly improving resistance to axial splitting under shear loading [485]. The slab systems include CLBT beamless slab, CLBT joist slab and regular joist slab. For lateral load resistance, the structural system integrates V-shaped buckling-restrained steel braces in conjunction with bamboo bracing along the horizontal axis, while lightweight shear walls are deployed along the vertical axis to improve in-plane stiffness and stability [486]. Moment-resisting beam-column

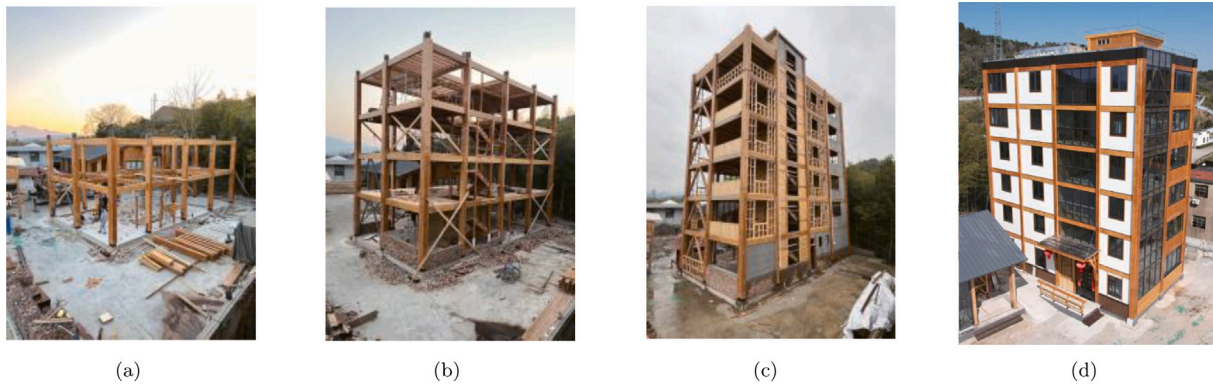


Fig. 35. The assembly construction process of the seven-story bamboo structure. (a) First and second floor construction unit; (b) third and fourth floor construction unit; (c) completed seven-story structural frame; and (d) completed building. Adapted from Wu et al. [486].

connections are achieved using slotted-in steel plate joints, which are designed to provide adequate rotational stiffness and facilitate energy dissipation during seismic events [486,487]. The Ninghai Bamboo Tower exemplifies a comprehensive approach to structural design that addresses material anisotropy, connection reliability, and seismic resilience, thereby advancing the practical viability of engineered bamboo in mid- to high-rise construction.

5.3.5. Shells, domes, floors and roof structures

Recent decades have seen increased use of round bamboo in expressive, long-span architecture, thanks to its sustainability credentials [488]. Bamboo's hollow geometry and exceptional axial capacity lend themselves to shells and gridshells that carry loads mainly through in-plane compression and shear. Gridshells assembled from short culms or strips joined by universal nodes permit free-form surfaces with efficient material use. Greta Tresserra's hypar roofs in Cali, Colombia, and modular node systems enabling arbitrarily long continuous members illustrate this versatility [489,490]. The prominent examples are briefly reported below.

Several built examples illustrate the architectural and structural potential of round bamboo. The ZERI Pavilion at Expo 2000, reported as the first bamboo structure to receive a German building permit, covered about 2000 m² and received approximately 6 million visitors [491]. The ZCB Bamboo Pavilion in Hong Kong (Fig. 36a) further demonstrated the feasibility of expressive long-span bamboo shell structures and received wide international recognition [18,288]. Other notable examples include the "Arc" Gymnasium at Green School in Bali, a 14 m parabolic truss spanning 19 m [492], and the Panyaden International School Sports Hall in Thailand, a 782 m² lotus-inspired hall constructed with prefabricated bamboo trusses without steel reinforcement [493]. More recently, the Grand World Phu Quoc Welcome Center in Vietnam used approximately 42,000 bamboo culms to form large interlaced domes and arches, showing the scalability of traditional bamboo joinery [494]. These projects show the increasing acceptance of round bamboo in contemporary architecture. However, exposed and untreated culms remain vulnerable to insect and fungal attacks, and their service life can be very limited. Preservation methods such as borax-boric-acid soaking, smoke curing, and heat treatment are therefore essential for durable applications [216]. In parallel, grading rules and joint testing protocols in countries such as Colombia, Ecuador, India, and China have helped support the use of structural bamboo in regulated construction.

Laverde [495] presented the INBAR Garden Pavilion, known as "Bamboo Eye", as a representative example of contemporary round bamboo architecture (Fig. 36b). Designed for the 2019 Beijing International Horticultural Exposition, the pavilion integrates architecture and landscape through a "Garden-Pavilion" concept inspired by Lucio Fontana. Structurally, it demonstrates the potential of round bamboo through

32 m span arches assembled from more than 5000 bamboo culms. The project also highlights how traditional bamboo craftsmanship can be combined with modern engineering to support low-carbon architectural design.

Pei et al. [496] presented the design, construction, and full-scale testing of an engineered bamboo-timber composite gridshell (Fig. 36c). The 12.4 × 12.4 m doubly curved structure was formed through active bending, avoiding the need for prefabricated curved members. The system combined two lower softwood layers, two upper laminated bamboo layers, and one diagonal laminated bamboo bracing layer, thereby utilizing the flexibility of laminated bamboo and the compressive capacity of softwood timber. Parametric form-finding was carried out using Rhino and Grasshopper. Full-scale loading tests, including a 3-ton local area load, showed a linear elastic response, time-dependent creep, and residual deformation after unloading. Laser-scanning-based point clouds further confirmed the global deformation pattern and load redistribution capacity. The study demonstrates the feasibility of bamboo-timber composite gridshells for lightweight and low-carbon architectural applications.

Li et al. [497] proposed a nail-laminated bamboo-timber (NLBT) panel composed of glulam boards and sawn boards made from fast-grown Chinese fir, connected by nails along their wide faces. In this hybrid system, the stiffer glulam laminations attract a larger share of the load and help redistribute forces after the local failure of weaker timber boards, thereby reducing their adverse effect on the overall panel performance. Static bending tests on twelve NLBT specimens with different cross-sectional configurations and spans showed that NLBT panels are an economical and feasible approach for using local fast-grown timber in structural components [497]. Building on this concept, Shan et al. [498] developed nail-laminated bamboo-timber-concrete composite (NLBTCC) panels for floor systems, in which a lower NLBT panel is connected to an upper concrete slab using horizontal connectors. Bending and vibration tests indicated that NLBTCC panels with these connectors can satisfy the load-bearing and serviceability requirements for residential and office floor applications [498,499].

Recent studies have demonstrated the potential of glulam roof trusses and bamboo-steel hybrid systems for lightweight structural applications. Shi et al. [500] investigated planar roof trusses with riveted glulam joints connected through thin-walled steel tubes (Fig. 37a). Full-scale cyclic tests and OpenSeesPy-based hysteresis modeling showed stable cyclic behavior, with joint performance strongly governed by the geometry of the steel tube fasteners. Thinner tubes improved energy dissipation and post-yield deformation capacity, whereas thicker tubes increased peak strength but reduced ductility. These results highlight the importance of connection detailing in controlling failure mechanisms. Earlier full-scale tests on bolted glulam trusses by Xiao et al. [501] also showed that global behavior is sensitive to joint configuration and fabrication accuracy. In addition, Wu and Xiao [502] proposed

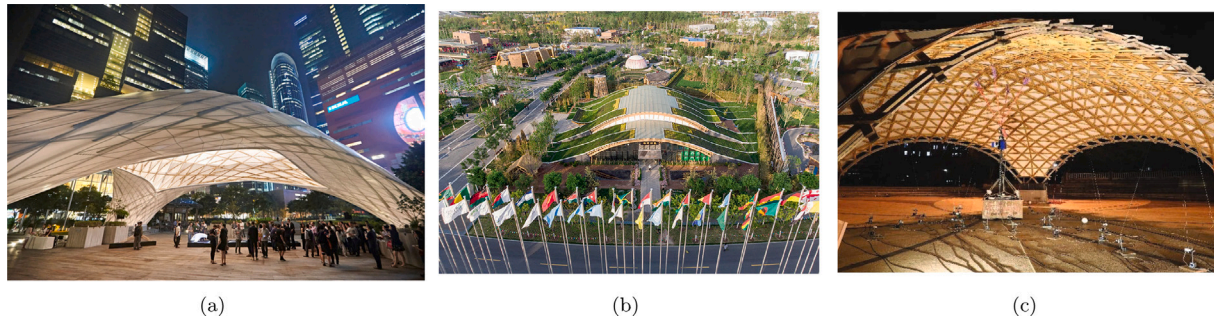


Fig. 36. (a) ZCB bamboo Pavilion. After Crolla [288]. (b) Aerial view of INBAR Pavilion. After Laverde [495]. (c) bamboo-timber gridshell loading experiment set-up. After Pei et al. [496].

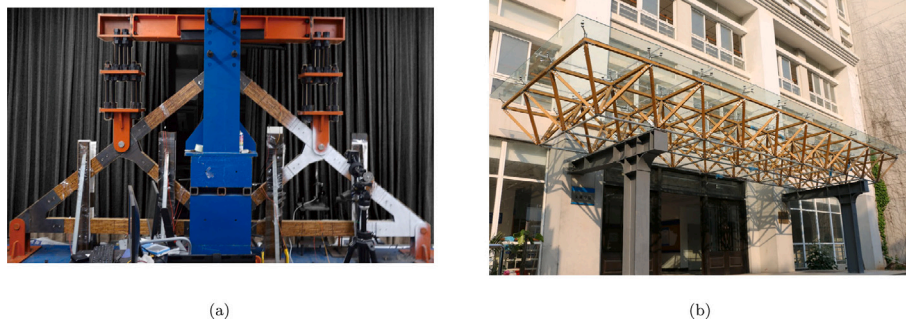


Fig. 37. (a) Test setup of glulam roof truss with riveted connections. After Shi et al. [500]. (b) Example project of bamboo-steel composite space truss structure. After Wu and Xiao [502].

a bamboo-steel composite space truss composed of glulam upper chords and diagonals with steel lower chords (Fig. 37b), which was applied as a rain-shed canopy for an office building. Quaranta et al. [503] further evaluated the dynamic performance of this structure, recommending a damping ratio of 1.5% and confirming adequate vibration serviceability for minor footbridge applications. Overall, these studies show that glulam and bamboo-steel truss systems can provide viable solutions for lightweight, prefabricated, and low-carbon structural applications.

5.3.6. Other applications (e.g., formwork, composites)

Beyond primary load-bearing roles, bamboo's versatility allows for its use in several ancillary construction applications, such as temporary formwork, scaffolding, and as a constituent in advanced composite materials. These uses exploit bamboo's low weight and renewability but also involve distinct challenges related to durability, dimensional stability, and standardization.

Attempts to employ round bamboo as reinforcement in structural concrete—dating back nearly a century [14,384,504]—have been comprehensively evaluated and largely deemed impractical [270]. As demonstrated by Archila et al. [270], bamboo's low elastic modulus (approximately 7–13 GPa, less than one-tenth of steel's ≈ 200 GPa) results in excessive deformation and cracking when used as tensile reinforcement. To achieve comparable crack control to steel-reinforced concrete, the bamboo-reinforced section would require reinforcement ratios exceeding 3.5%, leading to uneconomical member sizes. In their portal-frame design example, bamboo-reinforced members required cross-sections 260–300% larger than steel-reinforced equivalents, consuming substantially more concrete. Consequently, a life cycle assessment revealed almost double the embodied carbon (approximately 2000 kg CO₂ eq) relative to the steel design (approximately 1100 kg CO₂ eq), primarily due to the higher concrete volume [270]. These findings demonstrate that, despite its renewability, bamboo is not a viable or sustainable substitute for steel in conventional reinforced-concrete systems [270].

Bamboo's application in formwork systems (Fig. 38a), however, presents a practical and environmentally advantageous alternative to conventional timber or steel panels. Experimental studies confirm its suitability for reusable concrete formwork, with laminated panels achieving sufficient flexural strength and stiffness for temporary load-bearing applications [342,505]. Moreover, bamboo's flexibility enables the fabrication of complex molds through active-bending techniques, as demonstrated in adaptive gridshell formwork for thin concrete shells [506]. These systems highlight bamboo's potential in sustainable, low-carbon construction. Nonetheless, challenges concerning dimensional stability, moisture resistance, and surface precision remain critical. Improved resin impregnation, sealing treatments, and lamination quality control are essential to ensure durability and consistent casting performance [216].

The development of bamboo-based composite members represents another significant area of application, where bamboo fibers or laminates are used as reinforcing elements in polymer [507], cementitious [508], or steel-based matrices [509–511] to create high-performance hybrid components (Fig. 38b). These composites leverage bamboo's inherent properties, such as its high strength-to-weight ratio and biodegradability, to create materials suitable for various sectors, including construction, automotive manufacturing, and packaging [512]. Research has focused both on understanding the mechanical behavior of the fiber-matrix interface under working loads [511] and on enhancing composite performance through fiber treatments such as alkali modification, enzymatic processing, and other surface functionalization techniques to improve interfacial bonding and load transfer efficiency [513].

5.4. Research questions for structural systems

- How can engineered bamboo structural systems—including moment frames, braced frames, and shear walls—be optimized for lateral stiffness, strength, and seismic resilience to facilitate the



Fig. 38. (a) Bamboo permanent formwork during the casting of concrete. After Akmaluddin et al. [505]. (b) Bamboo-steel composite beam specimens. After Li et al. [510].

design and construction of code-compliant and economically viable mid- to high-rise buildings? [181,479,480,484]

- What are the most effective strategies for designing and standardizing robust, ductile, and easily manufacturable connections for both round and engineered bamboo that can ensure reliable load transfer, provide predictable energy dissipation, and prevent brittle failure modes, particularly under cyclic loading? [279,329,400,417,442]
- How can the unique mechanical properties of bamboo, such as its high tensile strength and flexibility, be harnessed through advanced computational design and fabrication to create efficient and expressive high-rise or long-span structures? What is the extent of the architectural design solution space that is practically feasible within today's technology and construction context, and how does its expansion allow for novel architectural design outcomes? [18,19,288,488,489,495,496]
- What are the long-term structural implications of creep, fatigue, and environmental degradation on engineered bamboo components and their connections, and how can accurate predictive models be developed to ensure the durability and service-life performance of permanent bamboo infrastructure like bridges and buildings? [216,379,464]

6. Indoor environmental quality

Indoor Environmental Quality (IEQ) is a multidimensional determinant of occupant health, comfort, and productivity, governed largely by the physical and chemical interactions between building materials and the indoor climate [514,515]. Unlike inert conventional materials, bamboo is a biologically active, porous material. Its unique microstructure—comprising vascular bundles and parenchyma cells—exerts a substantial influence on the thermal, hygrothermal, acoustic, and air-quality conditions of the built environment.

This section analyzes the key properties of bamboo that define these environmental performance metrics, transitioning from physical regulation (thermal, sound, moisture) to chemical safety (air quality).

6.1. Thermal properties

The thermal performance of building materials describes how materials respond to heat transfer, and is commonly evaluated using parameters such as thermal conductivity, thermal resistance, thermal transmittance (U-value), specific heat capacity, and thermal diffusivity [516]. These properties govern a material's ability to insulate, store heat, and maintain thermal stability, directly influencing energy efficiency and indoor comfort.

Bamboo exhibits favorable thermal characteristics, including good thermal insulation, low conductivity (0.05–0.20 W/(m·K)), and moderate heat storage capacity [367,517]. Its anisotropic structure leads to

higher conductivity longitudinally than radially. These values are significantly lower than those of conventional materials such as concrete (≈ 0.8 W/(m·K)) [518] and steel (≈ 33.6 W/(m·K)) [519], underscoring bamboo's suitability as a building insulator. Additionally, its specific heat capacity (≈ 1.4 kJ/(kg·K)) [520] supports thermal mass behavior, helping to moderate indoor temperature fluctuations. Bamboo also shows a moderate thermal expansion coefficient (between -6.67 and -8.33×10^{-6} /K) [521], contributing to its dimensional stability under temperature variations.

These properties stem from bamboo's inherent microstructure—a porous, fibrous composite of cellulose, hemicellulose, and lignin—that inhibits heat flow, particularly in radial and tangential directions [218,367]. However, the transition from natural bamboo to engineered bamboo introduces an important trade-off. Engineered products such as laminated bamboo lumber, bamboo scrimber, and fiber composites often exhibit higher thermal conductivity because densification and resin addition reduce porosity and increase solid conduction pathways. From a thermal-envelope perspective, this means that the same processing steps that improve mechanical performance generally move the material away from the behavior of an insulator and toward that of a denser structural component [367].

Density significantly influences bamboo's thermal performance. As illustrated in Fig. 39(a), a strong positive correlation exists between density and thermal conductivity across bamboo and bamboo-based materials ($R^2 = 0.793$) [517,522–531]. Higher-density products such as bamboo scrimber therefore exhibit increased thermal conductivity due to reduced porosity and enhanced solid conduction pathways, consistent with heat-transfer theory in porous media [532]. This is structurally advantageous but thermally disadvantageous when the objective is insulation. In this respect, densified engineered bamboo differs from lighter structural softwoods and should not be interpreted as a high-performance insulating material simply because it is bio-based [367,387].

From the standpoint of building operational energy, this trade-off should be interpreted at the system scale rather than at the material scale alone. In heating-dominated climates, envelope insulation remains the dominant control on conductive heat loss, whereas the impact of thermal inertia on energy demand is generally secondary and often limited to only a few percent [533]. Dense engineered bamboo should therefore be combined with dedicated insulation rather than relied upon as the principal thermal barrier. This conclusion is supported by bamboo-specific envelope research: in an analysis of laminated bamboo lumber and bamboo scrimber wall systems across five climate zones, 121 mm of insulation was recommended in severe cold regions and 77 mm in cold regions, while no insulation was required in the remaining three zones for the studied wall configurations [534]. Furthermore, it was found that external insulation systems performed better than internal insulation systems in the cold and severe-cold zones [534]. In warm, mixed, or tropical climates, dense bamboo elements may contribute beneficially to

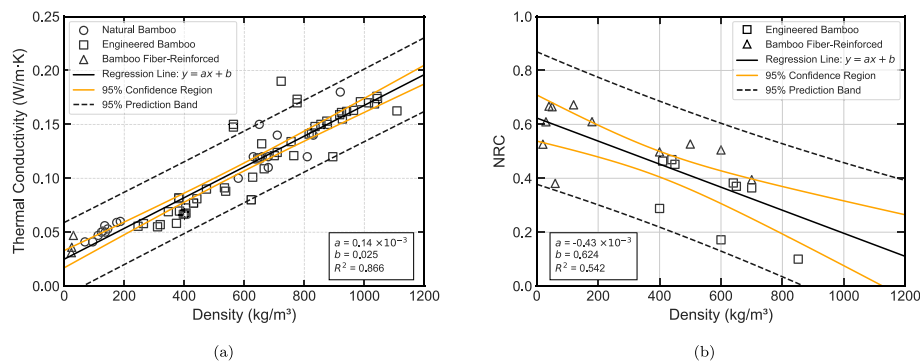


Fig. 39. (a) Thermal insulation performance of bamboo materials. Data from [517,522–531]. (b) Acoustic insulation performance of bamboo materials. Data from [535–539].

thermal inertia and indoor comfort, but this does not remove the conductivity penalty associated with densification. Accordingly, high-density engineered bamboo is best interpreted as a structural material within a layered envelope, not as a standalone insulating wall material.

6.2. Acoustical properties

Acoustical properties, including sound insulation and absorption, are critical in building materials, directly influencing indoor environmental quality, occupant comfort, and the acoustic performance of built environments. In acoustic evaluation, sound absorption is commonly quantified using the absorption coefficient (α), and the Noise Reduction Coefficient (NRC), which represents the average α at four mid-frequency bands (250, 500, 1000, and 2000 Hz). A higher NRC indicates greater sound absorption capacity. Sound insulation, on the other hand, is typically assessed using the Sound Transmission Class (STC) or Transmission Loss (TL), which reflect the material's effectiveness in preventing sound from passing through. Higher STC or TL values indicate stronger insulation performance. With the growing demand for sustainable construction, natural and renewable materials such as bamboo have received increasing attention not only for their mechanical and thermal characteristics but also for their acoustic potential [540].

The sound absorption mechanism of bamboo-based acoustic materials primarily relies on their natural porous structure and fiber distribution, which dissipate sound energy through friction within the pores and localized structural resonance, effectively converting sound into heat [541]. Bamboo fiber materials typically show better sound absorption at high frequencies ($\alpha \approx 0.7$ above 1000 Hz) and moderate absorption in the mid-frequency range ($\alpha \approx 0.3$ between 250–800 Hz), while performing poorly at low frequencies ($\alpha \approx 0.1$ below 250 Hz) [535,537,542,543]. Irvani et al. [542] proposed adding an air cavity behind bamboo-based panels to improve the absorption level at frequencies below 1000 Hz for bamboo-based panels. Koizumi et al. [537] confirmed this point and they concluded that the Sound Absorption Coefficient (SAC) with the whole range of frequency of bamboo-based panels can be further enhanced by optimizing their thickness.

Limited evidence indicates that densified engineered bamboo materials (such as glulam and bamboo particleboards) exhibit superior sound insulation performance. Kong et al. [538] investigated the acoustic properties of glued laminated bamboo (glulam) and spruce-pine-fir (SPF) using an impedance tube method. They found that glulam exhibits better sound insulation performance compared to SPF and other materials. Based on experimental results, Wen et al. [544] developed a finite element model to predict the sound reduction index of materials, demonstrating that composite structures and double-layer panels with intermediate cavities can effectively enhance the sound insulation performance of glulam or SPF. In particleboards made from bamboo shavings, the particle size significantly affects acoustic performance; smaller particles typically result in lower sound insulation metrics such

as Sound Transmission Class or Transmission Loss, but often lead to better sound absorption (higher SAC values) [536].

Fig. 39(b) illustrates the relationship between the Noise Reduction Coefficient (NRC) and material density for two categories of bamboo materials: engineered bamboo and bamboo fiber-reinforced composites [535–539]. The trend demonstrates a negative correlation (slope $a = -0.43 \times 10^{-3}$, intercept $b = 0.624$) between NRC and density, indicating that higher material densities are generally associated with lower sound absorption capacity, consistent with broader acoustic material behavior observed in natural fiber composites [537,545]. Bamboo fiber-reinforced composites consistently exhibit superior NRC values compared to engineered bamboo at equivalent densities, likely due to their more heterogeneous microstructure and internal porosity, which promote greater acoustic energy dissipation [546]. Regression analysis yields an R^2 value of 0.542, suggesting a moderate but statistically meaningful linear relationship. The inclusion of 95% Confidence Regions and 95% Prediction Bands highlights both the reliability of the regression model and the variability inherent in the material processing and measurement techniques. These findings imply that density optimization—particularly toward lower ranges—may be a viable strategy for enhancing the acoustic performance of bamboo-based materials in architectural and interior applications, particularly where lightweight, sustainable, and sound-absorptive panels are desirable [537].

Bamboo fiber is widely used for a variety of engineering applications to provide excellent acoustic properties with low-density composites. Huda et al. [547] developed a lightweight composite material composed of bamboo strips and polypropylene mesh, which exhibits favorable mechanical properties and acoustic performance. Farid et al. [548] investigated the sound absorption performance of polyester/bamboo fiber composites, reporting a high absorption coefficient of up to 0.97 at 1000 Hz. A bamboo-based polymer composite suitable for use as an automotive door panel sound-absorbing material was developed, exhibiting an average SAC of 0.411 across the 500–4000 Hz frequency range [549]. Pantjawi et al. [550] developed a low-cost sound-absorbing material from waste and bamboo fibers, which meets the ISO 11654:1997 standard as a Class E absorber with a weighted sound absorption coefficient $\alpha_w = 0.25$ (M).

6.3. Moisture buffering

From the perspective of IEQ, the inherent hygroscopic nature of bamboo is a double-edged sword. On one hand, similar to wood, bamboo can act as a natural moisture buffer in indoor environments. The abundance of hydroxyl groups within its cell wall polymers, primarily cellulose and hemicellulose, allows bamboo to absorb and desorb water vapor from the surrounding air, thereby moderating diurnal fluctuations in indoor relative humidity and contributing to latent heat exchange [526,551–553].

However, these benefits should be interpreted primarily for interior service conditions. Under variable-humidity or exterior environments, the same hygroscopicity becomes a durability and serviceability concern rather than a benefit. The moisture exchange manifests as swelling during absorption and shrinkage during desorption [554,555]. Due to bamboo's heterogeneous and gradient cellular structure, these dimensional changes are non-uniform. When deformation is restrained, differential strains develop across the section and generate internal moisture-induced stresses. In densified engineered products, these effects may be exacerbated because processing-induced compressive set and reduced porosity can intensify stress development during moisture uptake [556,557].

The implications are especially important for structural connections. In real members, swelling and shrinkage are partly restrained by bolts, dowels, steel side plates, bonded interfaces, and adjacent components. Under such restraint, moisture-induced deformation can generate stress concentrations perpendicular to the grain, promoting splitting, localized cracking, and progressive deterioration of load transfer. In addition, changes in moisture content can alter joint stiffness and strength and contribute to fastener loosening or modified embedment behavior over time. Direct quantitative measurements of swelling force in engineered bamboo connections remain limited. However, the underlying concern is supported by converging evidence from bamboo hygroexpansion studies, moisture-sensitive bond-interface studies in glued bamboo, moisture-dependent fastener/embedment behavior in bamboo scrimber, and timber analogues for restrained swelling stresses in joints and cross-sections [557–560]. Accordingly, moisture buffering should not be invoked as a generic advantage for engineered bamboo in exterior service.

6.4. Chemical safety and indoor air quality

Indoor chemical safety in bamboo-based construction is influenced primarily by preservatives, coatings, and adhesive systems used in engineered products. In particular, thermosetting adhesives such as phenol-formaldehyde resins are relevant to both formaldehyde-emission concerns and toxicity-oriented environmental assessment, especially during manufacture and early service life. Product-specific testing indicates that formaldehyde emissions can be controlled to accepted standards in laminated bamboo products. For example, thin-strip glulam specimens tested in a 1 m³ climate chamber remained below 0.124 mg/m³ and met Class E1 according to EN 13,986 [561] under the reported conditions [562]. This is further supported by evidence from a recent large-scale structural project, in which both thin-strip and thick-strip glulam were reported to satisfy the more stringent Class E0 formaldehyde-emission requirement under the reported test conditions [563]. Recent research has also explored adhesive-free and self-bonded bamboo bio-composites produced through innovative hot-pressing processes, with the aim of eliminating formaldehyde-related emissions and improving indoor air quality [564,565].

Beyond mitigating adhesive-related emissions, bamboo-derived materials offer active air purification solutions. Porous bamboo charcoal and activated carbon have demonstrated significant adsorption capabilities [566]. Functionalized bamboo charcoal, often modified with compounds like silver-doped titanium dioxide, effectively removes formaldehyde, other Volatile Organic Compounds (VOCs), and microbial contaminants such as bacteria and fungi [566,567]. Bamboo-based activated carbon, enhanced through various activation methods, exhibits improved capacity for gaseous formaldehyde and carbon dioxide adsorption, contributing to IAQ regulation and energy savings from reduced mechanical ventilation [568–570]. Moreover, bamboo charcoal composites are being developed to capture fine particulate matter (PM_{2.5}) [571]. It is noteworthy that thermal modification of bamboo, while improving durability (as discussed in Section 4.3.1), can introduce distinct odors (e.g., terpenes, alcohols) that affect IAQ [572].

6.5. Research questions for indoor environmental quality

- How do the thermal, acoustic, and hygroscopic properties of various engineered bamboo products interact under dynamic, real-world conditions? Research is needed to develop and validate coupled multi-physics models that can predict the integrated performance of bamboo-based building envelope systems, accounting for simultaneous heat, air, and moisture transfer [517,538,554].
- How can the microstructure of engineered and composite bamboo materials be strategically designed and manufactured to achieve targeted building physics properties? This includes tailoring density, porosity, and fiber orientation to optimize the trade-off between thermal insulation, thermal mass, sound absorption, and sound insulation for specific applications like acoustic panels or insulated wall assemblies [367,536,541].
- What are the quantitative effects of various durability-enhancing treatments (e.g., thermal modification, chemical preservation, fire retardants) on the thermal, acoustic, and moisture-buffering performance of bamboo? A systematic investigation is required to understand and optimize the multi-objective performance, balancing durability with building physics efficiency [573–575].
- How can engineered bamboo products be developed to actively enhance IEQ beyond simply minimizing emissions? This involves scaling up production of zero-VOC composites using advanced bio-adhesives or adhesive-free bonding techniques, and integrating functional materials like bamboo charcoal for passive air purification and humidity regulation [562,564,566,568].

7. Fire resistance, durability, and end-of-life scenarios for bamboo

7.1. Enhancing fire resistance of bamboo in construction

A critical challenge for bamboo in construction is its inherent flammability. Crucially, the fire performance of bamboo material cannot simply be equated with that of a bamboo structure, especially when engineered bamboo is proposed for mid- or high-rise buildings. Effective fire safety strategies must therefore advance on two fronts: the fire resistance of the bamboo material itself may be enhanced through physical, chemical, or thermal modification techniques, while at the architectural and structural design level bamboo is often integrated with other materials in composites or assemblies and must be detailed to limit fire exposure, preserve load-bearing capacity, and satisfy the relevant code pathway for combustible structural systems [476].

Assessing the fire resistance of bamboo construction materials relies on a suite of standardized testing methodologies designed to ensure that modified and treated bamboo products meet critical safety benchmarks. These tests evaluate various aspects of fire performance, including ignitability, flame spread, heat release, and smoke production. Cone calorimetry is a widely utilized technique that provides quantitative data on heat release rate (HRR), total heat release (THR), and time to ignition (TTI) under controlled heat flux conditions [258,576–589]. These parameters are fundamental for characterizing bamboo's flammability and assessing the efficacy of fire-retardant treatments. The Limiting Oxygen Index (LOI) test is another common method, determining the minimum oxygen concentration required to sustain combustion and providing a measure of a material's intrinsic flammability [578,580,581,586,590–595]. Furthermore, the UL94 vertical burning test, originally developed for plastics, is frequently adapted to evaluate the self-extinguishing behavior and flame propagation characteristics of bamboo-based materials, yielding classifications based on performance in vertical flame scenarios [578,580,584,586,587,590–594]. Beyond bench-scale assessments, researchers are increasingly employing larger-scale experimental setups, such as four-side fire tests [596], fire resistance tests under eccentric compression [576], and full-scale connection fire tests [597], to simulate more realistic fire conditions and evaluate the structural fire performance of engineered bamboo elements and assemblies. Collectively, these diverse testing methodologies provide a

Table 7
Charring rates of engineered bamboo and timber materials.

Reference	Material	Charring rate (mm/min)
EN 1995-1-2 (2004) [598]	Glulam with a characteristic density of $\geq 290 \text{ kg/m}^3$	0.65
GB/T 50708-2012 [599]	Glued laminated timber (1 h fire resistance)	0.76
AS/NZS 1720.4:2019 [600]	Hardwood and softwood	$0.4 + (280/\rho_{12})^2$
Xu et al. [365]	Bamboo scrimber	0.63
	Bamboo scrimber (perpendicular)	0.45
Chen et al. [601]	Laminated bamboo	0.58 to 0.88
	Bamboo scrimber	0.50 to 0.63
Xu et al. [602]	Laminated bamboo (flatwise)	0.98 to 1.08
	Laminated bamboo (edgewise)	1.02 to 1.08
Xu et al. [603]	Laminated bamboo	0.76

Note: In AS/NZS 1720.4:2019 [600], ρ_{12} denotes the material density at 12% moisture content, in kg/m^3 .

robust framework for evaluating and comparing the fire resistance performance of bamboo materials, guiding the development of effective fire mitigation strategies.

From a structural fire design perspective, engineered bamboo should be interpreted in relation to the better-established fire behavior of mass timber. Under EN 1995-1-2 [598], a one-dimensional charring rate of 0.65 mm/min is commonly adopted for glued-laminated timber with a characteristic density $\geq 290 \text{ kg/m}^3$, and this value is often used as a benchmark for comparison. Laminated bamboo lumber (glulam) and bamboo scrimber have reported charring rates ranging from 0.45 to 1.08 mm/min, with the values strongly dependent on product type, density, orientation, adhesive system, and test configuration. A comprehensive comparison is provided in Table 7.

A notable risk for densified and laminated bamboo products under fire loading is the delamination of adhesive bond-lines. Representative fire tests indicate that laminated bamboo beams can char faster than denser bamboo scrimber beams under three-sided standard-fire exposure [601]. In laminated bamboo lumber columns, flatwise specimens exhibited a two-stage response, with the charring rate increasing from about 0.86 mm/min to 1.075 mm/min after char-layer fall-off, whereas edgewise specimens maintained a steadier response without spalling [576]. More recent standard-fire tests on bamboo scrimber and glued-laminated bamboo further showed that phenol-formaldehyde-bonded specimens exhibited more pronounced delamination and spalling than polyurethane-bonded specimens, confirming that adhesive selection

materially affects fire robustness in densified bamboo composites [604]. These results indicate that mid- to high-rise bamboo applications should rely on conservative fire design, including sacrificial char layers, encapsulation and/or external protection, rather than on ambient-temperature section capacity alone.

As discussed in Section 4.3.2, surface coating and impregnation have already been introduced as two principal barrier and filling strategies for improving bamboo durability. Here, the focus shifts to their use in fire protection, together with chemical modification aimed specifically at enhancing flame retardancy.

Among these approaches, surface coatings provide a direct means of limiting flame spread and heat transfer at the exposed interface. Recent developments range from simple bio-based formulations to multifunctional hybrid systems. For instance, as illustrated in Fig. 40(a), Yu et al. [584] developed a hydrogel coating composed of methylcellulose, polyacrylamide, and tetraethyl orthosilicate-pretreated ammonium polyphosphate. This coating significantly increased the Limiting Oxygen Index (LOI) and reduced both the heat release rate (HRR) and total heat release (THR). Intumescent fire-retardant coatings, often formulated with ammonium polyphosphate and boric acid, have likewise shown strong potential for reducing peak heat release rate (PHRR) and suppressing smoke generation in bamboo-based bio-composites [577,582]. In addition, surface mineralization or infusion with minerals such as calcium carbonate (CaCO_3) [258] and clay mineral powder [587] can further improve fire performance by promoting protective barrier formation and enhancing char stability.

Impregnation treatments aim to improve fire resistance throughout the bamboo bulk rather than only at the surface. Immersing bamboo in flame-retardant solutions, particularly those containing ammonium polyphosphate (APP) and boron-based compounds, has proven effective in reducing combustibility and improving overall fire performance [579,605–608]. More recently, Ye et al. [588] explored pretreatment with ternary deep eutectic solvents (TDES), leading to the formation of phytates and sulfate-containing holocellulose nanofibrils (PHCNFs) with excellent flame-retardant characteristics. As shown in Fig. 40(b), these systems often exploit synergistic interactions among phosphorus, nitrogen, and boron (P-N-B), which promote char formation and suppress heat and smoke release during combustion [588,605,608,609].

A more advanced route is chemical modification at the molecular scale, which seeks to impart intrinsic flame retardancy directly to the bamboo structure. Representative strategies include phosphorylation [581], grafting flame-retardant functional groups onto bamboo polymers [595], and the in-situ synthesis of inorganic compounds within the cell wall [610,611]. Compared with coatings and impregnation, these

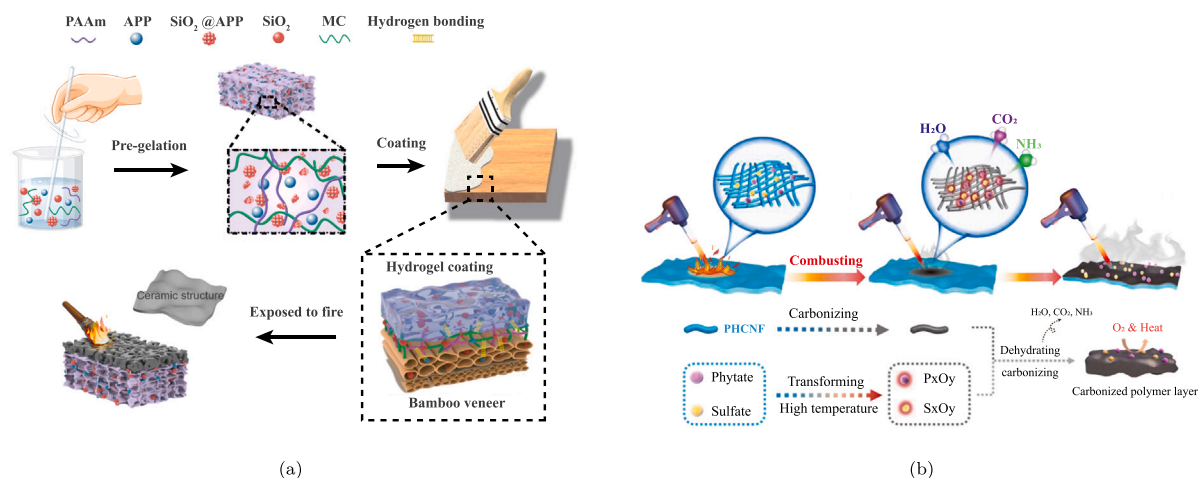


Fig. 40. (a) Schematic illustration of the flame-retardant function of the hydrogel coating. Adapted from Yu et al. [584]. (b) Flame-retardant mechanism of the PHCNF. Adapted from Ye et al. [588].

approaches are particularly promising for achieving more durable and potentially leach-resistant fire protection, which is important for maintaining long-term performance, especially in exterior or humid service conditions.

Beyond material-level treatment, effective fire safety in bamboo construction also depends strongly on system-level protective design. Code compliance for taller bamboo buildings is likely to require a combination of structural robustness, protected or encapsulated structural elements, limited exposed combustible surfaces in critical zones, automatic sprinklers, and project-specific fire verification, rather than relying solely on ambient-temperature material capacity [476,598]. In practical applications, shielding bamboo members from direct fire exposure is often more reliable and economical than relying on material modification alone. A representative example is the Cement-Bamboo Frame (CBF) shear wall system, in which the bamboo framing is fully embedded within a cement-based mortar matrix [466]. This protective encasement shields the bamboo from direct flame impingement and elevated temperatures, enabling the assembly to maintain load-bearing capacity for a substantially longer period during standard fire exposure and, in some cases, to satisfy regulatory fire-resistance requirements for wall systems [466,612]. Other widely adopted protective measures include fire-rated gypsum board cladding [613] and integrated fire detection and alarm systems [580,586].

7.2. Durability and lifespan of bamboo in construction

Both round and engineered bamboo structures are susceptible to material performance degradation over time in practical applications. The environmental and biological factors influencing bamboo durability, together with the principal preservation and modification strategies used to mitigate them, have been discussed in Section 4.3. Building on that material-level discussion, the present section focuses on the service life actually achievable in built structures. The longevity of bamboo construction varies significantly with exposure severity, design detailing, and treatment efficacy. While untreated bamboo typically exhibits a limited lifespan—often less than a few years when in contact with soil—due to its high susceptibility to biological degradation [614,615], properly treated round or engineered bamboo systems can achieve enhanced durability. Studies indicate that through appropriate modification and design, these materials can attain service lives comparable to softwoods and hardwoods used in construction [616,617].

Historical evidence from Latin America provides compelling proof of the material's potential for longevity. In regions such as Colombia and Ecuador, thousands of buildings constructed using the traditional bahareque technique remain in service today, with numerous documented examples having successfully survived for over a century [385].

However, despite these promising historical indicators, a systematic evaluation of the service life of modern bamboo structures remains largely absent from the scientific literature. Current understanding is predominantly derived from isolated case studies or accelerated laboratory aging tests, lacking a comprehensive framework for quantitative lifespan prediction [618,619]. Consequently, establishing standardized methodologies to quantitatively assess and model the long-term durability of bamboo systems represents a critical knowledge gap that requires further investigation.

7.3. End-of-life scenarios for bamboo

At the end of their service life, bamboo products and structural components generate a considerable amount of post-use bamboo waste. These materials usually originate from the demolition or replacement of bamboo-based elements in buildings and other infrastructure. With the construction and demolition sector accounting for approximately 35% of global solid waste generation, the rapid market expansion of engineered bamboo materials is anticipated to significantly contribute to this growing waste stream [620]. The recovery and recycling of post-use bamboo waste are essential for lowering life cycle carbon emissions and closing

the carbon loop in engineered bamboo systems [133,621]. The reviewed literature identifies several end-of-life pathways for bamboo waste, including landfill disposal, incineration for energy recovery, and material recycling.

7.3.1. Reuse: from waste to resource in a circular economy

Due to their high strength, rapid renewability, and biocompatibility, bamboo materials can be recycled and reused at the end of their service life. The recycling of bamboo waste generally involves physical and chemical methods to reintegrate the material into the production cycle, thereby conserving resources and reducing environmental impact.

Common physical recycling involves crushing or grinding discarded bamboo elements into smaller forms—such as chips, particles, or fibers—which are then reconstituted into new products like particleboards, decorative panels, or composite substrates. Other minimally processed methods involve transforming bamboo waste into agricultural bedding, handicrafts, and garden fencing. These methods effectively reduce material consumption and carbon footprint while diverting waste from landfills. Research indicates that properly treated bamboo waste retains substantial compressive and tensile strength, making it suitable for non-structural applications and interior design [622,623]. Furthermore, recycled bamboo fibers can be effectively used as reinforcement in Bamboo-Polypropylene Composites (BPCs). By combining these biological fibers with polymer matrices, the resulting materials offer enhanced properties widely used in the construction and packaging industries [624].

Chemical-based recycling focuses on extracting valuable components, particularly fibers, from the bamboo biomass. Through chemical treatments such as pulping, bamboo waste can serve as a raw material for producing recycled paper, textiles, or fiber-reinforced materials [625,626]. Additionally, under high-temperature and pressure conditions, bamboo waste can undergo thermochemical processes to yield renewable chemicals like furfural, acetic acid, and lignin derivatives. These compounds serve as important feedstocks for bioplastics and other green chemical industries [627–629].

Optimizing these recycling technologies and promoting their widespread application are crucial for improving resource efficiency. The integration of bamboo materials into a circular economy aims to ensure that every bamboo product follows a closed-loop system, minimizing waste generation at the end of its life cycle [630]. This conceptual system is visually represented in Fig. 41(a).

7.3.2. Energy gain and supply

When bamboo materials are no longer suitable for recycling or reuse, they still offer considerable value as bio-energy sources. Bamboo possesses a high carbon content (approximately 52.6%) and a calorific value ranging from 17 to 20.5 MJ/kg, comparable to that of wood, making it a viable renewable energy feedstock [631,632]. Direct combustion is the most prevalent method for energy recovery from waste bamboo. Bamboo can be utilized in boilers, kilns, and dedicated biomass power plants to generate heat energy for industrial processes or domestic heating [633]. However, incomplete combustion can release pollutants like carbon monoxide (CO) and fine particulate matter (PM_{2.5}), highlighting the need for efficient combustion technologies or the implementation of effective exhaust gas treatment systems to mitigate environmental impacts [634].

Producing bamboo charcoal through pyrolysis is a higher-value energy recovery method. Pyrolysis, typically conducted at temperatures between 300 and 700 °C in the absence of oxygen, converts bamboo into bamboo charcoal and liquid by-products such as bamboo vinegar [635]. Bamboo charcoal, owing to its high porosity and carbon content, finds diverse applications, including water filtration, air purification, soil amendment in agriculture, and even in the pharmaceutical industry. Bamboo vinegar, the liquid co-product, can be used as a natural pesticide or antimicrobial agent, supporting sustainable agricultural practices [635–638].

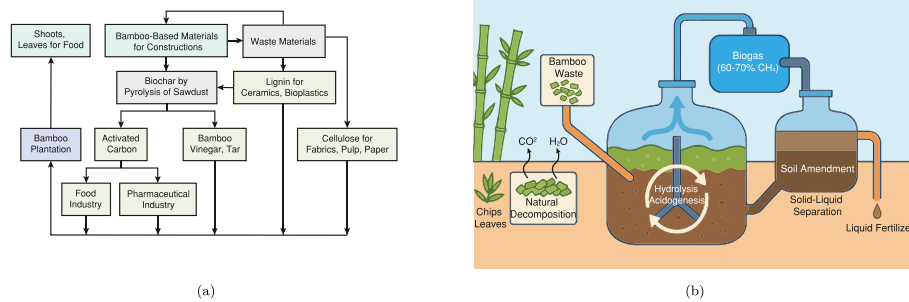


Fig. 41. (a) Reuse of bamboo material as part of the circular economy. Adapted from Yadav and Mathur [630]. (b) Typical anaerobic digestion process for biogas and organic fertiliser production from bamboo waste.

Additionally, bamboo can be processed through anaerobic digestion to produce biogas, a renewable fuel. As shown in Fig. 41(b), the typical anaerobic digestion process involves microbial decomposition of organic matter under oxygen-deficient conditions. In the case of bamboo, its primary components (cellulose and hemicellulose) can be broken down by microorganisms to generate methane (CH_4) and carbon dioxide (CO_2) [633,639–641]. However, the relatively high lignin content in bamboo can reduce its overall biodegradability in anaerobic digestion, a limitation that can often be overcome or improved through appropriate pretreatment techniques, such as hydrothermal treatment combined with H_2SO_4 [642].

In summary, energy recovery from bamboo waste offers a valuable pathway for reducing waste disposal volumes while providing a sustainable energy source. However, continuous optimization of combustion, pyrolysis, and anaerobic digestion technologies is necessary to enhance energy conversion efficiency and minimize potential environmental pollution.

7.3.3. Landfilling: a least preferred option

Landfilling of waste bamboo materials is generally considered the least preferred option due to its environmental implications and low resource value. As a natural biomass material, bamboo is biodegradable under environmental conditions [133]. Its main constituents (cellulose, hemicellulose, and lignin) decompose at varying rates; cellulose and hemicellulose degrade relatively quickly through microbial action, while lignin is much more resistant, taking years to decades for full degradation [643]. Under anaerobic landfill conditions, bamboo degradation can generate methane (CH_4) in addition to carbon dioxide, and these methane emissions may offset a substantial portion of the temporary carbon-storage benefit otherwise attributed to bamboo products [644]. Global waste management policies are increasingly moving toward restricting organic waste from landfills, as evidenced by regulations in regions like the EU and China [645–648].

At the same time, landfilling remains the default or only available waste-management route in many regions. Its environmental consequences must be explicitly accounted for when evaluating the life cycle performance of bamboo materials. In such cases, mitigation measures such as landfill-gas recovery systems and soil-remediation technologies are important for reducing environmental impacts [648–651]. A transparent accounting of the biogenic carbon flows should be included when conducting the life cycle assessment. The assumptions regarding landfill-gas capture and methane management should be stated explicitly, since they materially influence the resulting climate assessment.

7.4. Research questions on fire, durability, and end-of-life

- How can the fire performance of bamboo and engineered bamboo products be reliably predicted and further enhanced through novel, environmentally friendly treatments and composite designs,

considering the diversity of bamboo species and intended applications? [14,258,576,577,580,584,588,610]

- What are the most effective integrated strategies for protecting bamboo construction materials against biological decay, light degradation, and hygrothermal effects to ensure long-term structural integrity and service life in diverse climatic conditions? [443,652–658]
- How can circular economy principles be optimally applied to bamboo construction waste through effective recycling, chemical valorization, and bioenergy recovery methods, maximizing resource efficiency and minimizing environmental burdens compared to traditional disposal pathways? [622,624,625,627,630,635,639,643,659,660]

8. Policy landscape: enabling bamboo in sustainable construction and carbon reduction

Reducing construction-related emissions requires wider use of low-embodied-carbon materials. Bamboo combines rapid growth, renewability, relatively low embodied energy, and substantial carbon sequestration potential, making it a promising option for decarbonizing the building sector, a major contributor to global greenhouse gas (GHG) emissions [661–665]. Realizing this potential, however, depends on supportive and effective policy frameworks that can overcome technical and institutional barriers and guide a transition toward more sustainable construction practices [663–665]. In this sense, wider adoption of bamboo is closely aligned with several Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) [36,661–679].

National and international policies have begun to acknowledge bamboo's potential role in sustainable construction. Nevertheless, research consistently highlights the need for targeted governmental support to overcome substantial barriers, especially in emerging economies [665, 667,668,677,680,681]. These barriers include the absence of national building codes and design standards, insufficient technical expertise among construction professionals, and a persistent public perception of bamboo as a temporary or inferior building material [665,667,668,677, 680,681]. Supportive policies are therefore indispensable for addressing these challenges and creating an enabling environment for bamboo construction [665,667,668].

Building on the existing literature, several key policy levers can be identified to effectively promote bamboo in construction:

- **Implementation and enforcement of building codes.** For the manufacturing and structural design of bamboo construction products, several international standards have been established [195, 386]. However, only a few countries have incorporated bamboo into their national building codes or localized these ISO standards for regulatory use. Developing, adapting, and enforcing national codes and certification systems that explicitly recognize bamboo

can legitimize it as a reliable structural material, thereby strengthening confidence among engineers, architects, and builders [665,667,668,672,673,680–682].

- **Government programs and financial incentives.** Integrating bamboo construction into national housing and rural development programs, coupled with subsidies, tax incentives, or low-interest loans, can help offset initial costs and perceived risks. Such financial instruments encourage investment, stimulate demand, and make bamboo construction more accessible and attractive to both public and private stakeholders [673,676,681,683–685].
- **Support for research, development, and capacity building.** Investing in research is crucial for improving processing techniques, developing innovative bamboo products, and generating robust data on material properties and long-term performance. This must be complemented by targeted training programs for architects, engineers, builders, and forest managers to enhance technical knowledge and overcome construction-specific challenges [665,667,668,672,673,680,681,686–689].
- **Certification and sustainable sourcing.** Policies that support the development and implementation of bamboo forest certification schemes are vital for ensuring sustainable harvesting practices and long-term resource availability. Certification enhances the credibility, environmental profile, and market appeal of bamboo products and can link them to green public procurement and eco-labeling schemes [687,690–694].
- **Public perception and awareness.** Overcoming the perception of bamboo as a temporary or “poor man’s material” is essential. Government-led awareness campaigns, the promotion of flagship modern bamboo projects, and public education initiatives can help shift attitudes, build trust, and increase acceptance of bamboo as a durable, safe, and aesthetically pleasing building material [36,665,667,668,674,677].

As detailed in Section 1.2, bamboo construction systems can achieve favorable, and in some boundary conditions net-negative, life cycle carbon balances when sustainably sourced and properly designed. Policies that recognize and reward low-embodied-carbon solutions—for example through performance-based building codes, carbon budgets, or green public procurement—therefore provide a direct lever for substituting high-carbon materials such as concrete and steel and aligning the construction sector with national climate strategies and SDG 13 [36,662–666,670,671,678,679,682,695,696].

Beyond climate action, policies promoting bamboo construction can also support decent work and economic growth (SDG 8) by fostering local bamboo industries and providing training and capacity building, particularly in rural communities where bamboo is cultivated and processed [687,697–710]. They contribute to sustainable industrialization and innovation (SDG 9) through the development and adoption of engineered bamboo products, advanced processing techniques, and low-carbon building practices [36,661–665,667,668,672,673,710–712]. Finally, policies related to sustainable bamboo forest management and resource utilization support responsible consumption and production (SDG 12) and the protection of life on land (SDG 15) [675,687,690–694].

Economic evidence for engineered bamboo is best interpreted through functionally equivalent structural case studies rather than generic material-price comparisons. Available studies show that its competitiveness depends on the structural application, benchmark material, and market context. For example, case-based assessment of a steel-glulam hybrid truss in China found that environmental advantages did not correspond to a uniform economic advantage, while comparative studies on glulam and steel members likewise show that relative cost performance varies with member type and design assumptions [503,713]. In addition, broader analyses indicate that market barriers, industrial maturity, and policy conditions continue to influence the economic viability of bamboo construction [665,714]. Engineered bamboo should

therefore be regarded as a potentially cost-competitive structural material whose economic performance remains project-specific and strongly dependent on manufacturing scale, standardization, labor intensity, and recognition of low-carbon benefits.

8.1. Research questions on policy and market

- What are the most effective policy instruments and financial incentives for overcoming technical barriers (e.g., lack of standards, processing techniques) and market barriers (e.g., cost competitiveness, limited supply chain) to the widespread adoption of bamboo in construction [665,667,668,672,673,676,677,680,681,683–685]?
- How can research and capacity-building initiatives be strategically designed to improve technical knowledge among construction professionals and address public perception challenges regarding bamboo’s durability, safety, and suitability for modern building applications [36,665,667,668,674,677,680,681,686–689]?
- How can the carbon sequestration potential of various bamboo species and management practices be accurately quantified and standardized to integrate bamboo effectively into carbon accounting frameworks and climate mitigation policies for the built environment [36,146,617,662–666,670,671,678,679,682,683,695,696,715,716]?
- What are the socio-economic impacts of promoting bamboo construction, particularly in rural communities, and how can policies ensure equitable benefits, job creation, and sustainable livelihoods [687,697–710]?

9. Concluding remarks

This paper has reviewed a vast body of interdisciplinary research on bamboo as a sustainable construction material, connecting its fundamental biology to its performance in advanced structural systems and its role in life cycle carbon mitigation. By consolidating knowledge across materials science, forestry, engineering, and policy, this work underscores bamboo’s significant potential to contribute to a low-carbon, circular, and resilient construction industry. The transition from a traditional, vernacular resource to a mainstream engineered material is well underway, driven by technological innovation and a growing imperative for sustainability.

9.1. Main findings

This review has traversed the entire life cycle of bamboo in construction, yielding several key findings that encapsulate the current state of the art and future trajectory of the material:

- The journey begins with the unique biology of bamboo, a fast-growing perennial grass with a hierarchical, functionally graded structure (see Section 2). This structure supports its favorable strength-to-weight ratio and is fundamental to optimizing its use and developing next-generation, bio-inspired materials.
- Bamboo’s environmental credentials are built upon its rapid renewability and the ecosystem services provided by bamboo forests. With harvest cycles of just 3–5 years, bamboo offers significantly higher land-use efficiency than traditional timber. Its cultivation supports soil stabilization, water regulation, and substantial carbon sequestration, both within the forest biomass and, crucially, as locked-in carbon within durable building products. From a life cycle assessment (LCA) perspective, bamboo-based materials generally demonstrate a markedly lower carbon footprint than traditional construction materials. Sustainable forest management and robust certification are paramount to ensuring that these benefits are realized without adverse ecological impacts.
- The limitations of round bamboo—irregular geometry and property variability—are now being addressed through industrial processing. This review has detailed the critical processes of drying,

preservation, and lamination that transform bamboo into reliable engineered products such as glulam and bamboo scrimber. Advanced treatments are enhancing durability, fire resistance, and dimensional stability, making it possible to design and specify bamboo with the same rigor as conventional materials. These innovations are repositioning bamboo from a “poor man’s timber” to a high-performance, competitive building resource.

- The structural applications of bamboo have evolved dramatically from traditional low-rise dwellings to sophisticated, long-span, and multi-story structures. A critical enabler of this evolution has been the development of reliable connection systems, from improved techniques for round bamboo to standardized, high-capacity joints for engineered products. Inspired by advancements in mass timber, researchers are now developing ductile, energy-dissipating connections and hybrid systems (e.g., CLBT), paving the way for bamboo’s use in taller, seismically resilient buildings.
- Beyond structural strength, bamboo offers favorable building-physics performance, including good thermal and acoustic insulation properties. Its hygroscopic nature, however, remains a key challenge that requires careful management through design and treatment. Critically, bamboo fits seamlessly into a circular-economy model. At its end of life, it can be reused, mechanically or chemically recycled into new products, or used for clean energy recovery, minimizing waste and extending its environmental benefits.

9.2. Directions for future research

While significant progress has been made, realizing bamboo’s full potential requires a concerted and strategic research effort. This review has identified several critical areas where future investigation is needed to overcome remaining barriers and accelerate adoption:

- Future work must deepen our understanding of the complex relationships between bamboo’s hierarchical structure and its mechanical and physical properties. This requires advanced imaging and testing at the nano-, micro-, and macro-scales, coupled with the development of sophisticated multi-physics models. Such models are essential for accurately predicting long-term performance, including creep, fatigue, and response to environmental loads, thereby enabling more reliable and efficient designs.
- Research should focus on optimizing manufacturing processes for engineered bamboo to reduce energy consumption, minimize waste, and enhance performance. A key priority is the development and scaling of environmentally benign treatments for durability and fire resistance. This includes exploring novel bio-based adhesives, advanced thermal and chemical modification techniques, and multifunctional coatings that offer long-term, leach-resistant protection without compromising sustainability.
- An important emerging research direction is the application of engineered bamboo in mid- and high-rise construction. This requires a focused effort on developing and standardizing high-capacity, ductile structural systems. Research should prioritize the design and experimental validation of innovative connections, composite members (e.g., bamboo–timber hybrids), and lateral load-resisting systems (e.g., rocking shear walls) that can meet the demands of modern seismic and wind design codes.
- There is a need for a more holistic assessment of bamboo’s contribution to building performance. This involves investigating the integrated hygro–thermo–acoustic behavior of bamboo building envelopes and developing bamboo-based materials that actively enhance indoor environmental quality (IEQ), for example, through passive humidity regulation and air purification.
- Robust, comparative life cycle assessments (LCAs) are needed to quantify the environmental footprint of various engineered bamboo products against conventional and other bio-based materials. These data are critical for informing evidence-based policy. Future

research should also explore effective policy instruments, certification schemes, and economic models that can de-risk investment, address social barriers, and create robust, equitable supply chains to support a global bamboo construction market.

By addressing these research needs collaboratively, the scientific and industrial communities can unlock the full potential of bamboo, establishing it as a cornerstone of a sustainable, resilient, and low-carbon built environment for the twenty-first century.

Note to reader

Despite our comprehensive efforts to review and include all available and relevant literature on the use of bamboo as a construction material, it is possible that some pertinent studies or data may have been inadvertently overlooked. We encourage researchers and experts who are aware of additional information that could enhance, refine, or confirm the findings presented in this review to contact the authors. If deemed appropriate, an addendum to this paper may be prepared to incorporate such contributions and further enrich the discourse on this important topic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available upon request.

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