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Bamboo-based composites: A review on fundamentals and processes of bamboo bonding

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ABSTRACT

Sustainable development and applications of bamboo and bamboo-wood composites require better understanding and optimization of bamboo bonding. This paper provides a critical review of bamboo composite bonding in relation to wood bonding characteristics and processes. A polylamellate cell wall structure, low tissue porosity and permeability, and poor surface wettability hamper bamboo bonding with most wood adhesives. Bamboo element preparation, treatment and adhesive modification must be optimized in conjunction with more efficient material utilization and processes. Development of bond qualification standards similar to engineered wood products but tailored to stronger bamboo tissues are essential for structural bamboo composites. While phenolics are still commonly used for structural bamboo composite bonding, the industry is shifting away from formaldehyde systems. Isocyanate-based resins offer viable solutions, especially for bamboo strand composites. Changes in bamboo surface pH and wettability after industrial treatments like bleaching and pressure-steaming likely explain the variations in bonding performance with common wood adhesives. Hybrid bamboo-wood composites are promising cost-effective approaches for the engineered bamboo industry leading to viable building products. Future research subjects related to bamboo composite bonding are also discussed.

1. Introduction

Bamboo is rapidly renewable, biodegradable [1,2], useful for land rehabilitation [3,4] and carbon sequestration [5,6]. Compared to wood, bamboo culms are hard, strong, flexible and wear-resistant [7,8]. All these characteristics make bamboo a viable supplement to dwindling global timber supplies for applications in traditional furniture and new bio-based industrial and building applications (Fig. 1). Over the past 40 years, a wide range of bamboo composites have been developed, most notably bamboo scrimber [9–11], laminated bamboo [12,13], ply bamboo [14,15], bamboo strand-based composites [16,17] and bamboo winding composite pipes [18,19]. Studies by Cheng et al. [20] and Semple et al. [21] have demonstrated the production of hybrid bamboo-wood composites.

However, many bamboo composites, such as scrimber, cannot be classified and used as engineered composite building materials. They are still highly variable in properties and quality and do not meet the full suite of properties specific to acceptance under existing wood structural design and performance criteria. In addition, the round, hollow geometry of the culm and non-uniformity of structure make processing costly and inefficient relative to wood [23]. These unique characteristics create manufacturing challenges requiring greater attention to element preparation, adhesives and process control. Current industry practices and lack of quality control standards limit many bamboo composite products to traditional applications such as flooring and decking.

Publications on bamboo composites have increased significantly over the past two decades, with a concurrent increase in the sub-topic of bamboo bonding (Fig. 2). The strength and durability of bamboo bonds [15,24] and bamboo-wood bonds [25,26] play a critical role in the performance of the resulting composite products [27–29]. The natural variations in bamboo permeability, density, and chemical composition create unique challenges for bamboo bonding with adhesives, which are designed for wood products. Compared to wood adhesion, bamboo bonding is generally much more difficult and poorly understood. To the authors' best knowledge, only two review papers [30,31], both in Chinese, have been published directly considering bamboo bonding. These

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papers covered bamboo treatments and adhesive modification but did not expand on the fundamentals and processes of bamboo bonding.

This comprehensive review addresses both the bonding mechanisms and processing routes to improving bamboo adhesion, while considering the more effective utilization of bamboo in sustainable, structural composites. The main objectives of this paper are: 1) to highlight the similarities and differences between wood and bamboo characteristics pertaining to adhesive interactions and bonding processes, 2) to elucidate techniques to improve the surface properties and bonding performance of bamboo, and 3) to identify challenges and knowledge gaps in the manufacturing, testing and performance of engineered bamboo.

2. Bamboo and wood characteristics affecting bonding

2.1. Adhesive chemistry

This section focuses on the introductory chemistry of phenol-formaldehyde (PF) and polymeric diphenylmethane diisocyanate (pMDI) adhesives as they affect adhesive interaction with bamboo tissue and bonds strength as discussed in Section 3.4.2. According to Frihart [32], wood adhesives can be classed into two groups based on their chemical and mechanical attributes: in-situ polymerized and pre-polymerized adhesives. Among the in-situ polymerized resins are PF and formaldehyde-free adhesives such as pMDI. These resins are generally composed of small molecules (monomers) when applied to wood or bamboo constituents, helping resin wetting and penetration. With time and often aided by elevated temperature, the monomers turn into large molecules (oligomers and polymers) as the resin cures to become a rigid, highly cross-linked polymer. With external pressure, the resin-cured and infiltrated wood/bamboo assemblies form close-contact, rigid bonds. Pre-polymerized adhesives, such as polyurethanes (PUR) and cross-linked polyvinyl acetates (PVAc), consist of

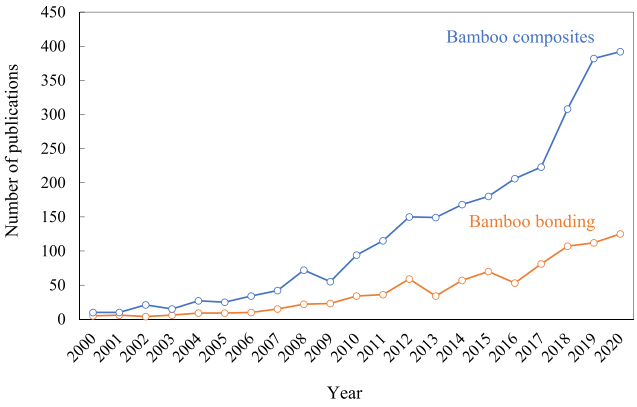


Fig. 2. Publication trends in bamboo composites and bamboo bonding from 2000 to 2020. Data collected from the Web of Science Core Collection using the keywords: "bamboo composites" or "engineered bamboo" for the bamboo composites trend and "bamboo adhesion" or "bamboo bonding" for the bamboo bonding trends.

Fig. 1. Bamboo composites in non-structural and building applications: (a) bamboo ceiling of Madrid Airport, (b) engineered bamboo columns on a building, (c) close-up of laminated bamboo lumber. [Sources: (a) and (b): International Bamboo and Rattan Organisation (INBAR; www.inbar.int) [22]].

large molecule polymers during application. These adhesives have limited mobility to penetrate wood or bamboo adherends but form more flexible bonds [32]. Flexible bond lines are beneficial to combat stresses associated with swelling or shrinkage, leading to greater bond durability. This section focuses on the introductory chemistry of PF and pMDI adhesives as they affect adhesive interaction with bamboo tissue and bonds strength as discussed in Section 3.4.2.

PF adhesives are alkaline (pH: 7 to 13), water-based (55–60% solids) formulations with a viscosity range of 150–600 cP at 25 °C according to the application for which the resin is destined [33]. Standard pMDI, whose viscosity varies from 160 to 350 cP at 25 °C based on industrial data, is an oil-based, 100% solids formulation and neutral in pH. The main benefits of pMDI, especially for manufacturing bamboo fiber and strand-based composites, include its ability to uniformly wet surfaces, good penetration depth into less porous and permeable bamboo, and fast curing speed (i.e., high reactivity of isocyanate groups compared to formaldehyde groups in PF adhesives). Additionally, depending on the application, pMDI generally cures at temperatures around 90–109 °C [34], while PF curing range is higher, between 120 and 230 °C [33]. pMDI adhesives are very effective since they can penetrate the wood cell wall forming 'chemical bridges' of urethane and biuret structures via covalent bonds with bound water and hydroxyl groups in wood and bamboo cell wall components [35,36].

Variation in wood species and age mixture causes variation in surface pH and buffer capacity, which creates more bonding challenges (lower cure speed and bond performance) for PF adhesives than with pMDI. Bamboo processing is far more uniform in terms of species and age mix (culms cut at 4–6 years from monocultures) and structural bamboo composites such as scrimber are successfully manufactured using a modified PF system. pMDI is highly effective for low-dose, spot-welded strand-based composites than continuous bondlines [17,25].

2.2. Mechanism of bamboo bond formation: adoption of Marra's model

There has been significant evolution in understanding the theories and mechanisms of wood bonding [37–41]. According to Marra [37], wood bond formation involves five interconnected phenomena: surface wetting by the liquid adhesive, adhesive spreading, transfer between cells, penetration, and solidification (polymerization). Wood and bamboo are both lignocellulosic materials similar in chemical composition (Section 2.7). Therefore, the fundaments of bond formation in wood may be considered applicable to bamboo [15,42–44]. However, some essential differences can affect bamboo bonding.

A schematic representation of a bamboo to bamboo "glueline" is shown in Fig. 3a and a more detailed representation of the "bondline" concept from the Marra model [37] is shown in Fig. 3b. The solid circles represent either the bamboo (circle 8,9) or adhesive phase (circle 1), or the physical interface between the two (circle 4,5), and the dotted circles represent the interaction between the solid phases of bamboo and adhesive, i.e., the surface and adhesive (circle 2,3) or subsurface and adhesive (circle 6,7). It is these so called 'interphases', zones 2,3 and 6,7 that are the most vulnerable to bond malformation [37] and subject to

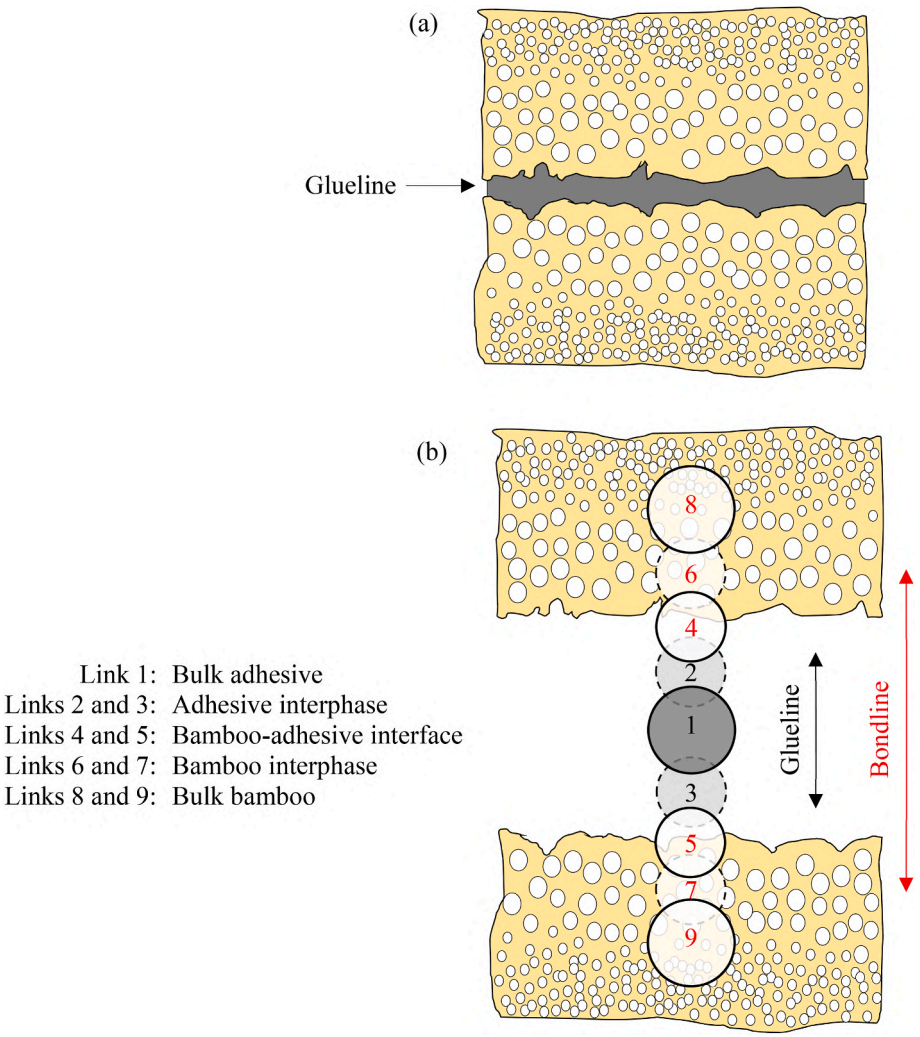


Fig. 3. Schematic representation of inner-inner glued bamboo: (a) glueline (links 1 to 3) and (b) bondline (links 1 to 7), adapted and modified from Marra [37].

greater focus in this review. Bond formation/malformation in these 'interphase' zones is affected by the adherend natural cellular structure (porosity, permeability), element surface preparation (splitting, incising, sanding, crushing, planing, etc.), presence of cut cells, macro and micro-cracks and fissures, and surface chemistry as affected by the organic compounds in and lining the cell lumen surface (hydrophilic hemicellulose or hydrophobic extractives), surface aging and oxidation, and physical and chemical treatments discussed in Section 3. The bamboo-adhesive interface (4, 5) is affected significantly by adhesive penetration depth [42,44] and the type of bonds formed between the surface hydroxyl groups (-OH) and the functional groups in the adhesive during cold/hot pressing. In turn the penetration depth and types of bonds formed depend on circle 5 – adhesive phase, i.e., adhesive type and chemistry, its viscosity, gel/cure and flow dynamics as affected by fillers/viscosity modifiers, and cure chemistry. Bond malformation at the adhesive phase can in turn be affected by antagonistic surface pH or oxidation state, and inappropriate curing conditions such as heat, time, and applied pressure.

According to Pizzi [38], secondary forces (e.g., hydrogen bonds and van der Waal's forces) appear to be the predominant mechanism for bonding wood. These and micro-mechanical interlocking between cured resin and pores in the adherend surface create the 'bond' which ideally should be stronger than the adherend tissue and capable of transferring shear or tensile stress to ensure a high degree of 'wood-failure' during a bond qualification test. These are discussed further in relation to bamboo in Section 5. Certain adhesives such as pMDI and low molecular weight (MW) PFs are believed to be able to chemically interact and form interlocking bridges analogous to 'plugs' or 'nails' with polymeric

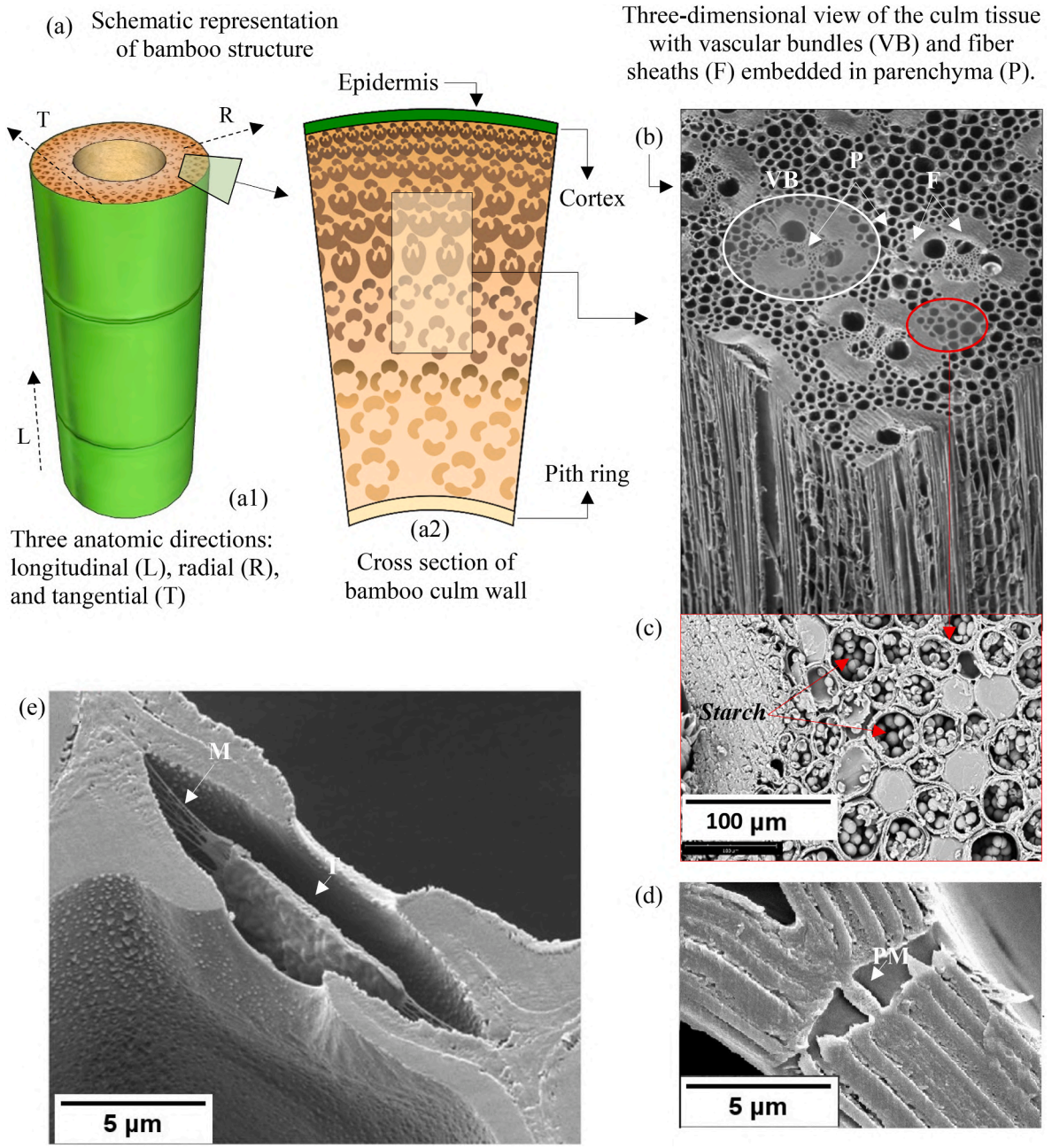


Fig. 4. Microstructural differences between wood and bamboo: (a) Schematic and (b) SEM micrograph of Moso (*Phyllostachys edulis*) bamboo, (c) starch grain occlusions in Moso, (d) SEM cross-section through the parenchyma cell walls of Moso showing small pit membrane (PM) and polylamellate cell wall structure, and (e) softwood (*Abies sachalinensis*) tracheid pit membrane showing typical porous margo (M) and solid torus (T). [Sources: (b) adapted from Liese [48], (d) Lian et al. [49], and (e) Sano [50]].

constituents in the wood cell wall [44]. Since the polymers (lignin, cellulose and hemicelluloses) constituting the cell wall of wood and bamboo are broadly similar, the bonding theories of Marra [37] are considered to be applicable to bamboo, even though the structure of bamboo cell wall is quite different to wood, as discussed in the next section.

2.3. Microstructure and anatomical differences between bamboo and wood

The increasing vascular bundle to parenchyma tissue ratio from the inner to outer culm wall makes bamboo a functionally graded composite material [45,46]. The outer cortex (skin) and inner pith wall of the culm (Fig. 4a1 and a2) have a strongly hydrophobic surface due to the presence of waxy and siliceous substances [47]. The waxy and siliceous substances protect the culm from drying out and against pathogens but also block or limit adhesive interactions with bamboo tissue. As shown in Fig. 4b, bamboo cells are all arranged in the longitudinal direction. The absence of ray cells in the transverse direction reduces lateral tissue porosity and permeability, contributing to poorer bonding performance compared with woods.

Bamboo parenchyma cells are also seasonally high in starch grains [42,53] (Fig. 4c), which reduce porosity and create blockages for adhesive penetration [54]. Industrial steaming [55,56] and boiling [54,57] treatments have been developed to reduce mould susceptibility, but may not remove starch entirely. Li et al. [54] found that boiling Moso bamboo in water reduced the percentage of pits blocked by starch but did not study the effect on bonding performance.

The primary reason for low penetrability by wood resins (particularly higher MW PFs) is the very small, impermeable pits connecting bamboo cells (Fig. 4d). These are the main channels through which fluids move laterally and differ from softwood pits in that they are much smaller and lack a porous margo structure (shown in Fig. 4e). Data in Table 1 from several studies indicate that despite the lumen diameters being similar between wood and bamboo, bamboo pits are about 7 times smaller than wood cell pits. A recent study by Liu et al. [58] using resin microcasting shows how bamboo pits are even less connected than they might appear in SEM micrographs. The parenchyma cells seen in Fig. 4b and later in Fig. 6a are connected via 'ramiform pits' that have very narrowed connecting channels between neighbouring pit cavities. These differences are likely to impinge on adhesive penetration and interactions with bamboo tissue compared with wood, as seen in Section

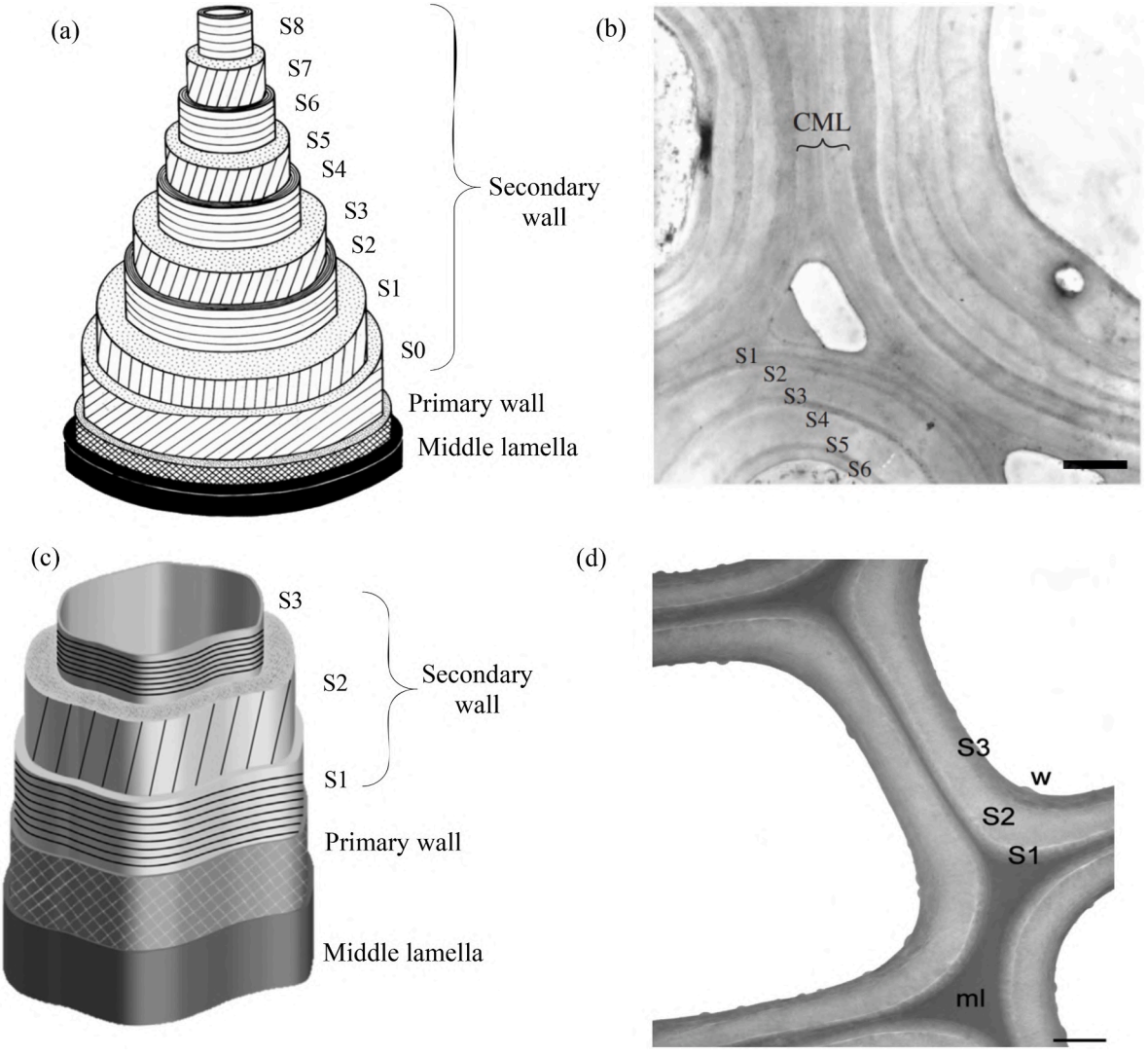


Fig. 5. Ultrastructure of bamboo and wood cell wall: (a) schematic model of the polylamellate structure of the bamboo fibre wall, (b) TEM cross-section of Moso bamboo fiber cell walls, (c) schematic model of the wood cell wall, (d) TEM cross-section of Radiata pine tracheid cell walls. [Sources: (a) adapted from Liese [48]), (b) adapted from Gritsch and Murphy [51], (d) adapted from Donaldson [52]. ML: Middle Lamella, W: Wart, CML: Compound Middle Lamella. Scale bars: (b) = 2 μm, (d) = 1 μm.

Table 1
Key anatomical characteristics of bamboo compared to wood.

Cell type	Cell characteristic	Average (μm)	Species	Reference
Parenchyma cell	Lumen diameter	10.4	Moso bamboo *(Phyllostachys edulis)*	Lian et al. [59]
	Pits aperture diameter	0.66–1.64		Lian et al. [60]
Fiber	Lumen diameter	1.61–7.40		Gan and Ding [61]
	Pits aperture diameter	0.11–0.28 (Inner layer) 0.14–0.29 (Outer layer)		Chen et al. [62]
Vessel element	Lumen diameter	113.23–139.66		Xiang [63]
	Pits aperture diameter	0.9–2.7 (Inner layer) 1.4–3.8 (Outer layer)		Liu et al. [64]
Vessel element	Lumen diameter	111.94–239.10	Red oak (*Quercus rubra*)	Helinska-Raczkowska [65]
	Pits aperture diameter	2.2–7.4	Japanese evergreen oak (*Quercus acuta*)	Saitoh et al. [66]
Fiber	Lumen diameter	6.6	Chestnut-leaved Oak (*Quercus castaneaefolia*)	Kiaei and Samariha [67]
	Pits aperture diameter	1.20–2.78	Teak (*Tectona grandis*)	Ahmed and Chun [68]
Ray parenchyma	Lumen diameter	12.59	Red oak (*Quercus rubra*)	Maeglin and Quirk [69]
	Pits aperture diameter	0.16–2.60	Teak (*Tectona grandis*)	Ahmed and Chun [68]
Tracheid	Lumen diameter	20.7–41.2	Douglas Fir (*Pseudotsuga menziesii*)	Schulte [70]
	Pits aperture diameter	15.0–21.2		
Ray parenchyma	Lumen diameter	8.09–11.41	Korean pine (*Pinus koraiensis*)	Ahmed et al. [71]
	Pits aperture diameter	4.61–24.41	Japanese red pine (*Pinus densiflora*)	
Resin canal	Lumen diameter	150–370	Slash pine (*Pinus elliottii*) Caribbean pine (*Pinus caribaea*)	Leggate et al. [72]

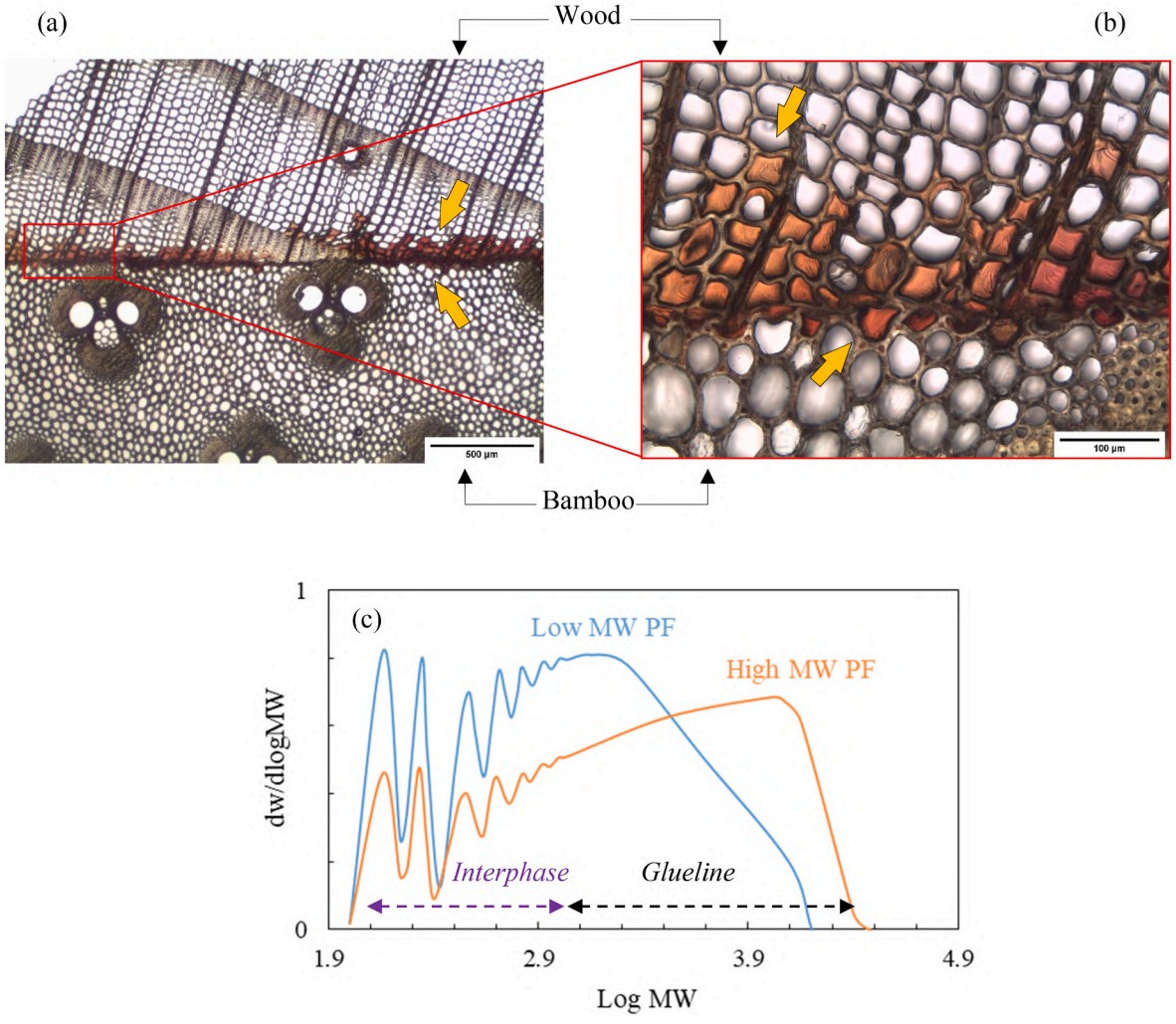


Fig. 6. Light microscopy images of bamboo-wood adherends bonded with mixed MW PF adhesive: cross-sections at (a) 500 μm and (b) 100 μm magnification; orange arrows indicate resin penetration, (c) concept of MW distribution in PF resin [73] in relation to bond formation. MW: Molecular Weight, PF: phenol-formaldehyde. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.4 Adhesive Penetration in Bamboo.

The polylamellate wall structure of bamboo parenchyma and fiber cell wall is shown Fig. 5a and b compared with the wood cell wall shown in Fig. 5c and d. The number of layers varies with bamboo species, within species, and cell type. According to Liu [74], these variations are related to growing conditions during the development of bamboo cells. A study on Moso bamboo by the author revealed that the number of cell wall layers increases as the culm ages from young to mature bamboo over the first 6 years, and decreases again after 8–9 years (senescence) as inner layers break down and detach from the cell wall. Parameswaran and Liese [75] observed up to 18 layers for Moso bamboo (*Phyllostachys edulis*) fibers, while Gritsch and Murphy [51] found up to 6 layers for the same species and cell type. In another recent study, Lian et al. [59] reported 11 layers in Moso bamboo parenchyma. Each layer has a perpendicular alignment of cellulose microfibrils [48,75–77]. The fine polylamellate structure may influence penetration and chemical interaction with adhesives, the efficiency of treatments, and bonding performance, as discussed later in Sections 2.4 and 3.4.

2.4. Adhesive penetration in bamboo

Studies [15,42,44] highlight the importance of adhesive penetration on bamboo bonding performance, which affects the integrity and performance of the resulting composites in service. However, the mechanisms of optimum adhesive penetration for bamboo remain poorly understood. Excessive penetration into large cracks and pores wastes adhesive and leads to starvation of the bondline [40]. The lack of penetration into bamboo cells (see Fig. 6a and b) also leads to low bond strength, especially with phenolic, urea and melamine adhesives that rely mainly on pore filling and mechanical interlocking. Structural adhesives have been carefully tailored (cure chemistry, pH, viscosity, gel times, and rigidity) to suit the fabrication of wood composite materials whose surfaces are pre-prepared primarily via some form of cutting or planing. Technical specifications and application guides such as application rates and compaction pressures from adhesive manufacturers are also developed for wood composites and may not be directly transferrable to bamboo. To this end, research has successfully customized wood adhesives to improve bamboo bonding discussed further in Section 3.4.3.

One strategy is to adjust the MW ratio in PF resin [24,44]. Fig. 6a and b shows an example of the differential penetration of mixed (50% low and 50% high) MW PF adhesive in a Moso bamboo-Douglas fir wood assembly. A schematic diagram of the concept of mixed MW distributions in PF is shown in Fig. 6c. Despite the mixed MW fractions, the penetration into bamboo was still far less (60 μm) than the wood (205 μm), likely due to the limited permeability and the dense polylamellate structure of the cell walls. Resin appears to have entered the interstitial spaces (corners) of the bamboo parenchyma cells, but not into any cells which are not cut open during surface preparation. While there is no published evidence yet, it may be postulated that the lower MW fractions of the mix could enter the interstitial spaces and perhaps migrate further to fill cell lumens away from the adherend surfaces (the wood or bamboo and adhesive interphases from Fig. 3b). The high MW fraction is more likely to have remained within the glueline zone (see Fig. 3) between the adherend surfaces.

Ma [78] measured the urea-formaldehyde (UF) adhesive penetration depth for a hybrid assembly of untreated Poplar veneer/bleached Moso bamboo strip. UF adhesive penetrated 12 to 24 times more in wood, indicating a significant difference in permeability to the adhesive between the two substrates. Bamboo permeability, especially in the transverse direction, is considerably lower than wood since it has no lateral conductive tissue (rays) and smaller pits, as shown in Fig. 4d and Table 1. There are no published reliable estimates of bamboo permeability using manometer measurements and Darcy's Law to quantitatively compare bamboo and wood permeability to air or liquids. Bamboo permeability, process-induced surface characteristics (i.e., element treatment, surface roughness, chemical activation, and moisture content), adhesive properties (i.e., molecular weight and solids content), and pressing parameters (temperature, time, and pressure) all affect adhesive penetration. Therefore, it is necessary to consider the correlation between these factors to better understand and improve bonding performance.

According to Kamke and Lee [40], adhesive penetration in wood is characterized by micro-scale and nano-scale penetration. This classification may be valid for bamboo with some essential differences, such as smaller pores and low connectivity compared to wood. Micro-scale water-based adhesive penetration in wood occurs via hydrodynamic flow then capillary action due to intermolecular forces between the liquid adhesive and surrounding hydrophilic lumen wall. The liquid adhesive flows through lumens and interconnected lumens and pits under external compaction pressure, with the polar adhesive seeking a new internal surface, e.g., lumen wall, to equilibrate positive and negative charges which effectively pulls the liquid column through the porous network. Frihart [39] proposed four different scenarios describing the mechanism of adhesive penetration into wood cell walls: 1) the adhesive occupies the free volume within the cell-wall, 2) mechanical interlocking effect as "fingers" of cured adhesive extend from the lumen into pits and other cell wall cavities, 3) interpenetration network made up of the crosslinked adhesive within the free volume of the cell wall, and 4) formation of chemical crosslinks with cell-wall polymeric components.

PF adhesive penetration on the nanometer level into the bamboo cell wall was investigated by Huang et al. [44]. It was explained by the nanomechanical interlocking of the cured resin within cell wall nano-voids and molecular interactions of the adhesive with bamboo polymers. The higher number of sub-layers in the secondary cell wall of bamboo could limit adhesive penetration on the nanometer level. However, the theories and mechanisms on adhesive interactions within the bamboo cell wall are still not well understood compared to wood and more fundamental studies are needed to advance understanding of bamboo adhesion and adhesives development.

2.5. Physical properties of bamboo

Compared with softwoods, the high specific gravity (SG) of bamboo and its variation across the culm wall can affect adhesive penetration, heat and moisture transfer during composites pressing [79,80]. A study by Febrianto et al. [81] shows a slight increase in internal bond (IB) strength with high-density bamboo used to make strands, since the substrate requires more force to rupture if the bond adequately transfers loading stress to the adjacent bamboo [82–85]. Dai et al. [80] and Frihart et al. [86] reported similar results using wood with different SG. Bamboo and wood elements used in hot-pressed composites have different compression ratios as they differ in density (i.e., SG) shown in Table 2), which in turn affects bond strength. Maulana et al. [87] produced oriented strand boards (OSB) from two bamboo species with different densities. They found a positive linear correlation between IB and compression ratio, since the contact area [88] and pressure [89] at the interfaces between strands increases which leads to better bonding and increased panel density. However, excessive compression ratio increases the thickness swell with water absorption due to greater compressive stress release [90]. Semple et al. [21] showed how during standard wood OSB pressing, bamboo strands did not compress like aspen wood strands, which changes the compaction ratio and strand surface contact pressures, leading to increased internal bond strength, and reduced moisture induced swelling behavior.

SG and shrinkage data from published papers for bamboo and wood in Table 2 indicate that bamboo tissue is higher in SG (1.8 times) and shrinkage (5.6 times) than commonly used hardwood and softwood species. These differences are related to the smaller pore structure and dense polylamellate structure of bamboo parenchyma and fibers [48,75]. Bamboo's high SG and shrinkage rates are critical factors to

Table 2
Specific gravity and shrinkage of bamboo compared to wood.

Physical property	Species			Average	Reference
Specific gravity[a]	Bamboo	Moso bamboo *(Phyllostachys pubescens)*		0.29–0.84	Li [91]
		Giant bamboo *(Dendrocalamus asper)*		0.55–0.90	Malanit et al. [92]
	Softwood	7 Fir species		0.30–0.43	Glass and Zelinka [93]
		5 Spruce species		0.35–0.42	
	Hardwood	2 Aspen species		0.38–0.39	
		3 Birch species		0.55–0.65	
Shrinkage[b]	Bamboo	Giant bamboo *(Dendrocalamus asper)*	Radial	6–11	Othman [94]
			Tangential	10–20	
		Common bamboo *(Bambusa vulgaris)*	Radial	4–9	
			Tangential	6–11	
	Softwood	7 Fir species	Radial	2.6–4.5	Glass and Zelinka [93]
		4 Spruce species	Tangential	6.8–9.2	
	Hardwood	2 Aspen species	Radial	3.3–7.3	
		3 Birch species	Tangential	6.7–9.5	

[a] Specific gravity: based oven-dry weight and volume at 12% moisture content.
[b] Shrinkage: green to oven dry.

consider when developing (a) customized adhesives for bamboo [24,42,44], (b) computer simulations for bamboo composites manufacturing [95,96] and (c) standard testing methods that evaluate bond durability as discussed later in Section 5.

2.6. Preparation of bamboo elements

The hydrophobicity of the bamboo skins (outer cortex and inner pith lining) leads to poor bond formation and performance, therefore requiring their total or partial removal or modification when preparing elements for composites. These processes, in turn, reduce the recovery rate shown for different types of bamboo composites in Table 3. Laminated bamboo is the most common bamboo product, made from rectangular milled elements without inner and outer cortex, and therefore has the lowest (35%) fiber recovery. Similar products can be manufactured using flattened bamboo sheets which are made from steam-softening and mechanical flattening of full or half culms. Although the inner and outer walls are removed, bamboo flattening produces much larger elements with significantly higher recovery (up to 55%) [97]. Conventional bamboo scrimber removes outer cortex, but uses heavily fissured or 'broomed' bamboo strips that are flexible and of naturally variable cross-sections allowing for width and thickness tapering [95]. Its fiber utilization rate (60–70%) is much higher than that of laminated bamboo. Bamboo laminated veneer lumber (BLVL) has the highest (90–95%) recovery, resulting from using both the variable element cross-sections and damaged or 'fiberized' cortex. The technique which allows for maximising recovery and creating a 'more bondable' element is also referred to as 'scrimming' [11]. Although the goal is to break up the surfaces for resin penetration, the mechanical action imposed on the bamboo strips from the incisor rollers often induce cracks and fissures that run through the entire culm wall thickness. As such, high resin dosage (up to 20% resin solids) and high compaction are needed to "repair" the damage and create a largely void-free composite lumber product. Disadvantages of this kind of product include very high density, and high chemical and energy consumption to manufacture.

Careful attention therefore needs to be paid to element preparation to optimize bonding, product density, and resin application and manufacturing efficiency. Smooth strand-based composites such as OSB and oriented strand lumber (OSL) offer an alternative solution that is more efficient in conversion, automation, and resin usage. Sun et al. [99] used bamboo strands and PF adhesive to fabricate OSL with different densities that were very effective in terms of strength properties relative to density compared with other types of bamboo composites such as scrimber. The modulus of rupture (MOR) and modulus of elasticity (MOE) of bamboo-OSL with a density of 0.78 g/cm^3 were 0.74 and 0.82 times those of bamboo scrimber (1.22 g/cm^3), respectively, and 1.55- and 1.28-times laminated bamboo lumber (0.68 g/cm^3), respectively. Conversion to long, thin, smooth, radially cut bamboo strands also maximizes recovery, retains the strongest fiber in the elements but restricts the cortex exposure to the narrow edges of strands, away from the bonding interphases [100,101]. Furthermore, bamboo strand-based oriented lumber products permit process automation and potentially significant reductions in resin usage but are not yet widely adopted by the bamboo composites industry [29,102].

Table 3
Recoveries and processing methods for different bamboo composites [97,98].

Type of bamboo composite	Density (g/cm^3)	Constituent element	Element processing method	Bamboo utilization rate (%)
Laminated bamboo (a)	0.66	Bamboo strips	Milled rectangular cross-sections with removed cortex and pitch.	35–40
Laminated flattened Bamboo (b)	0.70	Flattened bamboo sheet	Veneer from steam-softened, flattened culms with removed cortex and pitch.	50–55
Bamboo scrimber (c)	1.08	Bamboo bundles	Flattened, fissured strips with removed cortex.	60–70
Bamboo laminated veneer lumber (d)	1.12	Bamboo bundle curtain	Flattened, broomed strips with heavily modified cortex and pitch.	90–95


(a)


(b)


(c)


(d)

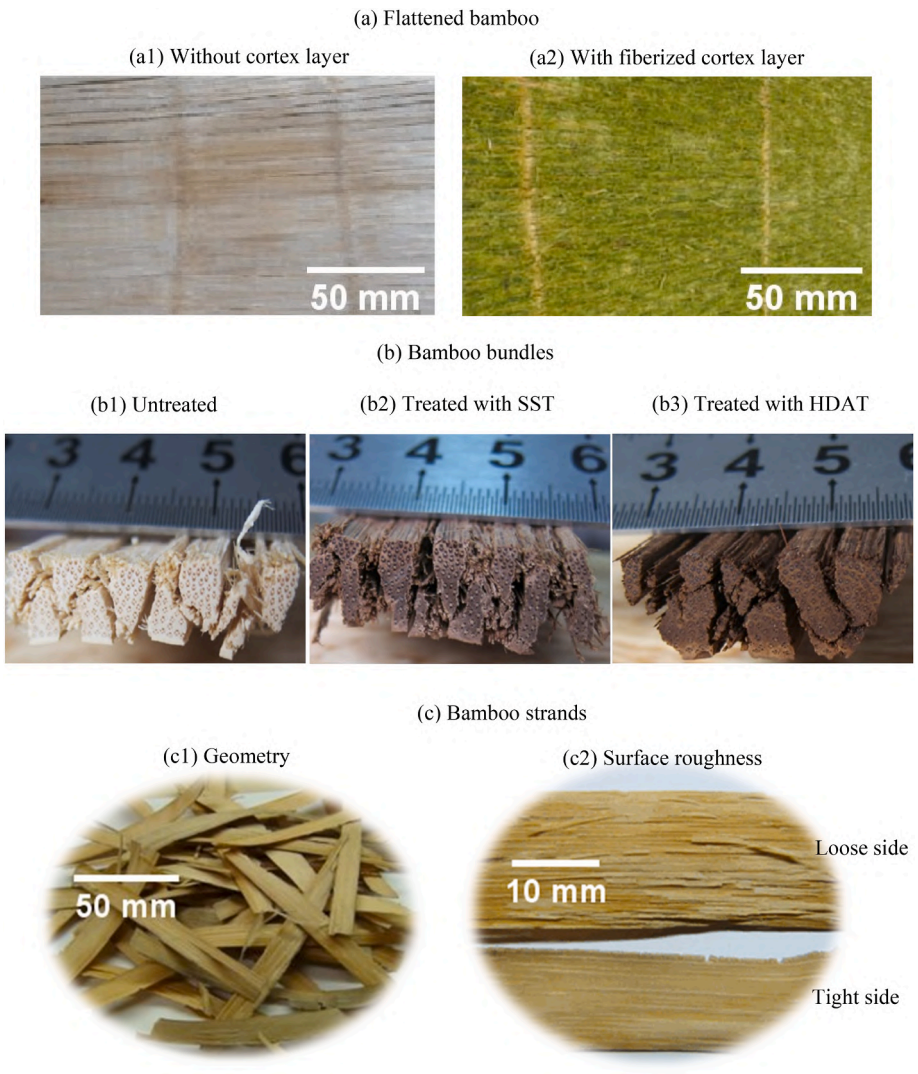


Fig. 7. Common types of constituent elements used to manufacture bamboo composites. Adapted and modified from (a1) Zhang et al. [103], (a2) Yu et al. [105], (b1-3) Yu et al. [11], (c1) Semple et al. [21], (c2) Semple et al. [104]. SST: saturated steam treatment, HDAT: hot dry air treatment.

2.7. Surface characteristics and chemical composition of bamboo elements

Fig. 7 illustrates element geometry and process-induced characteristics such as surface roughness, cracks, and heat treatment of bamboo elements which all influence the resin flow, penetration, bond formation and the performance of the resulting composites [11,103]. Aided by steam softening (140 °C), round bamboo culms can be flattened with few surface cracks. However at lower softening temperatures (100–120 °C) [103], cracks can develop which cause resin to migrate away from the bond line leading to resin starvation or excessive resin usage (Fig. 7a1). Newer versions of flattened bamboo (Fig. 7a2) roughen or 'fiberize' the surface for improved bonding without creating large deep cracks that consume more resin. Numerous very small cracks and fissures are necessary to break up the smooth, impermeable culm cortex. For some of the first-generation bamboo scrimber, excessive cracks are evident cross the culm wall (Fig. 7b1-3), reducing production and resin use efficiency. Fig. 7b2 and 3 also show the colour changes in bamboo bundles due to heat/carbonization treatments to improve dimensional stability and biodegradation resistance. These treatments can also interfere with resin spreading, penetration and bonding performance which will be discussed later. Geometric variations in bamboo strands (Fig. 7c1) can affect heat and moisture transfer affecting resin curing, and damage to the surface (Fig. 7c2) can result in reduced bonding strength and mechanical properties. Machining problems can cause variations in surface roughness (Fig. 7c2) of bamboo strands, e.g., machine settings and knife designs suited to wood can dislodge parenchyma tissue, causing a fractured surface, and require some adaptation for slicing bamboo to maintain element quality [104].

Table 4 summarises and compares published data on extractives content and key surface characteristics of untreated bamboo (without cortexes) and wood. Trends include higher acidity (~1.4 times) and buffer capacity (~2.8 times), and lower wettability (~1.3 times) of bamboo tissue, mainly related to its higher (~2.2 times) content of waxy and siliceous substances. Waxy substances, including waxes, fats, oils, and gums, are soluble in ethanol-benzene [47]. The presence of these substances reduces bamboo element surface wettability (i.e., contact angle >90° [106]). Treatments such as bleaching, and carbonization commonly used in the bamboo industry are used to adjust the color of elements (Fig. 7b1-b3) and improve mould resistance. These treatments affect the surface acidity and buffer capacity [107], changing its wettability and bonding performance at least with water-based resins, as discussed later in Sections 3.3 and 3.4.1. The variations in chemical composition and some key surface characteristics through the bamboo culm wall in Table 5 indicate that bamboo elements' location and inner/outer face can have variable adhesion characteristics, as

Table 4
Key surface characteristics and extractive content of untreated bamboo (without inner and outer layers) compared with wood.

	Characteristics	Average	Species		Reference
Acidity and buffer capacity	pH	4.8–6.66	Bamboo	Twenty-one Chinese bamboo species	Ma et al. [110]
		3.3	Wood	Douglas fir (*Pseudotsuga menziesii*)	Fengel and Wegener [111]
		5.8		Aspen (*Populus* spp.)	
	Buffer capacity	0.15–0.56	Bamboo	Twenty-one Chinese bamboo species	Ma et al. [110]
		0.03–0.09	Wood	Douglas fir (*Pseudotsuga menziesii*)	Fengel and Wegener [111]
		0.23–0.31		Aspen (*Populus* spp.)	
Wettability	Contact angle[a] (°)	52	Bamboo	Calcutta bamboo (*Dendrocalamus strictus*)	Ahmad and Kamke [112]
		62		Moso bamboo (*Phyllostachys pubescens*)	Shah et al. [113]
		38	Wood	Aspen (*Populus termitids*)	Freeman and Wangaard [114]
		51		Yellow poplar (*Liriodendron tulipifera*)	
	Total surface energy (mJ/m^2)	59.35	Bamboo	Calcutta bamboo *(Dendrocalamus strictus)*	Wang [115]
		68		Moso bamboo *(Phyllostachys pubescens)*	Shah et al. [113]
		35–85	Wood	Untreated woods	de Meijer et al. [116]
Extractives	Ethanol-benzene (%) to remove waxy substances[b]	1.60–4.78	Bamboo	Moso bamboo *(Phyllostachys pubescens)*	Jiang [117]
		4.45–10.15		Seven Indonesian bamboo species	Maulana et al. [47]
		4	Wood	Douglas fir *(Pseudotsuga menziesii)*	Rowell et al. [118]
		3		Quaking Aspen *(Populus tremuloides*	
	Hot water (%)	3.26–6.31	Bamboo	Moso bamboo *(Phyllostachys pubescens)*	Jiang [117]
		5.33–23.34		Seven Indonesian bamboo species	Maulana et al. [47]
		4	Wood	Douglas fir *(Pseudotsuga menziesii)*	Rowell et al. [118]
		3		Quaking Aspen *(Populus tremuloides*	

[a] Initial contact angle measured with water as probe liquid.
[b] Waxy substances.

Table 5
Data on chemical composition and key surface characteristics across the culm wall (middle section) of Moso bamboo. Adapted from Jiang et al. [119].

Characteristic	Outer layer	Middle layer		Inner layer
Chemical[a] composition	Cellulose (%)	67.67	68.38	63.02
	Hemicelluloses (%)	22.40	27.15	24.01
	Lignin (%)	27.90	24.01	23.68
Acidity and buffering capacity	pH	5.56	5.17	4.60
	Acid buffer capacity	7.24	9.20	5.10
	Alkali buffer capacity	13.58	13.21	12.95
Extractives	Ethanol-benzene (%) to remove waxy substances	3.81	5.72	4.80
	Hot water (%)	5.18	7.39	7.18

[a] Outer and inner layers do not include cortex and pith.

demonstrated in several studies [12,43,108,109].

3. Methods to improve bamboo bonding performance

3.1. Chemical and steam treatments

Bleaching with hydrogen peroxide (H_2O_2) and carbonization (pressure-steaming) treatments alter the composition and structure of bamboo polymers and surface bondability. Sharma et al. [113] found that lignin degradation is more pronounced in bleached bamboo than carbonized bamboo. Bleaching treatments have been shown to increase bonding strength [43,113,120]. In contrast, carbonization treatments can reduce bonding strength [113,121,122], as discussed later in Section 3.4.1. Carbonization treatment takes place in a vessel under 0.21–0.25 MPa pressure to 'pressure-cook' the bamboo at 120–130 °C for 4–8 h [123]. Carbonization is used by bamboo processors ostensibly to improve the mould/decay resistance of bamboo, and for colour modification. While decay resistance is reduced [124,125] ongoing research appears to show the starch grains responsible for mould resistance are not removed, and its optimal application in the bamboo industry is currently under investigation.

Bamboo bleaching takes place in an open vat containing a 27% hydrogen peroxide solution at a temperature of 70–80 °C for 4 h [123]. A disadvantage is that the hydrogen peroxide solution cannot be re-used or recycled between batches, creating a significant chemical waste disposal problem for bamboo processors [123]. Fatrawana et al. [126] and Maulana et al. [87] showed improved bonding and OSB strength, stiffness and dimensional stability if bamboo strands were washed with dilute sodium hydroxide solution after steam treatment.

3.2. Surface modification using physical methods

Surface modification using plasma, ultrasonic, and high voltage electrostatic field (HVEF), respectively illustrated in Fig. 8a, b, and c improve the bonding strength of bamboo [127–129]. These alter the surface roughness, chemistry, and permeability of bamboo [128–130] to improve bonding, as discussed later in Sections 3.3 and 3.4.1. To the authors' best knowledge, these treatments remain limited to laboratories and pilot plants because of their high cost and impracticality in the industrial setting.

During plasma treatment, highly charged particles create electric currents and magnetic fields, changing the material's surface chemistry [130], improving surface wettability and bonding strength, as shown later in Figs. 9 and 10, respectively. Several researchers [128,132] investigated the effect of ultrasonic treatment on bamboo bonding, showing the creation of micro-cracks in the cell walls and increased diameter of pores and pits, leading to better adhesive penetration and interaction, improving bonding performance. Unlike plasma and ultrasonic treatments, HVEF treatment is applied after adhesive application and during hot-pressing [133]. It causes polarization of the surfaces of lignocellulosic materials like wood and bamboo, generating free radicals that have greater reactivity with adhesive functional groups, enhancing bonding performance. HVEF treatment may also affect bamboo-adhesive interface (links 4 and 5 from Marra's model), influencing adhesive penetration into bamboo tissue. Physical treatments may be considered more environmentally friendly compared to bleaching. Their efficiency depends on various processing factors mentioned in Fig. 8a–c.

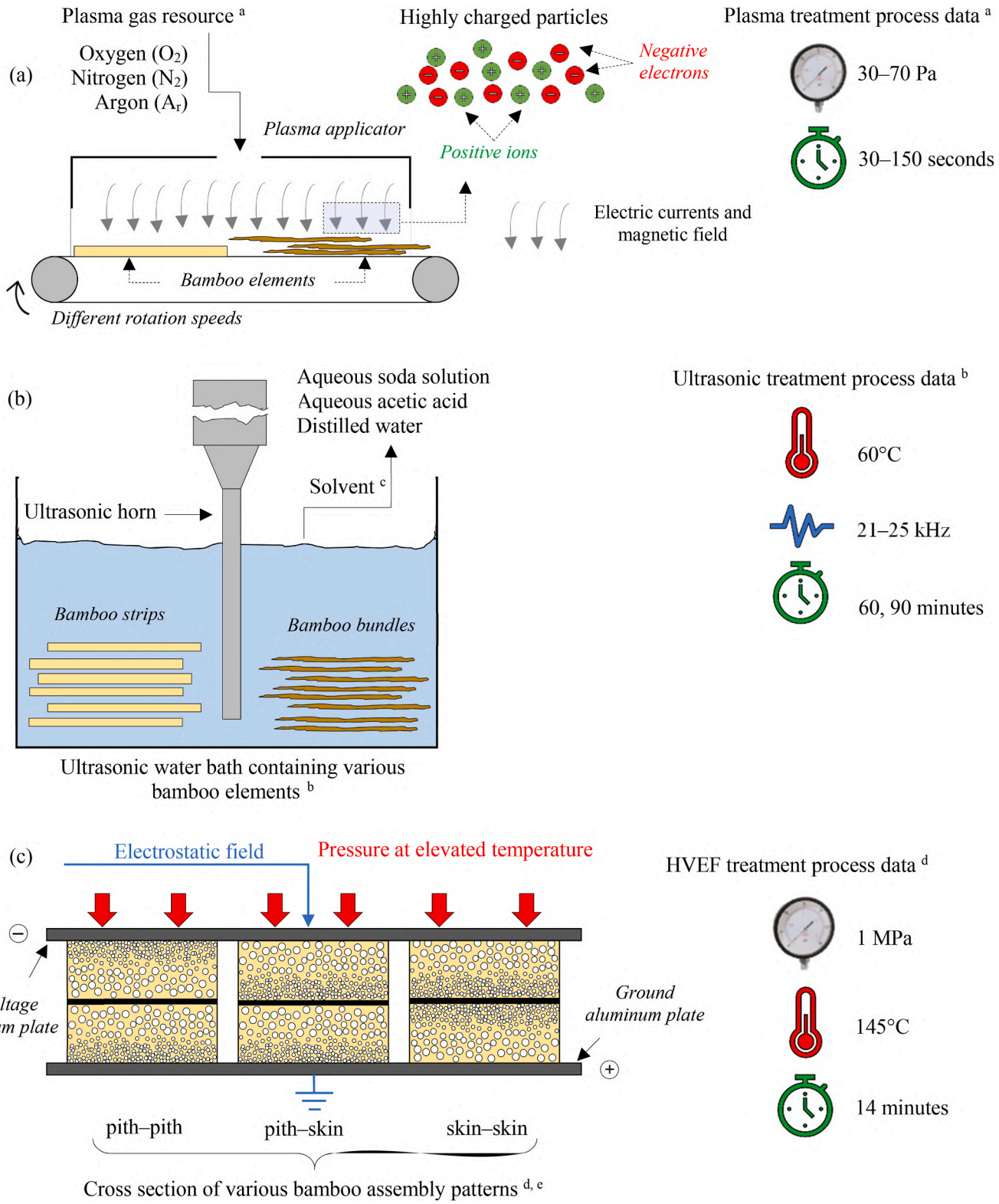


Fig. 8. Schematic representation of physical treatment of bamboo elements: (a) plasma, (b) ultrasonic, and (c) high voltage electrostatic field (HVEF); [a] Rao et al. [130], [b] Guan et al. [128], [c] He et al. [131], [d] He et al. [129], [e] Zheng et al. [109].

3.3. Effect of treatments on bamboo wettability

The percentage change in contact angle and surface energy of bamboo after bleaching, carbonization, and plasma treatments from published papers are shown in Fig. 9a and b. The comparative data indicate that bleaching and plasma treatments seem most effective at improving bamboo wettability, which might be expected to produce the most significant gains in bonding strength, as discussed later in Section 3.4.1.

Temperature above 130 °C and/or extended treatment time (above 8 h) during carbonization could reduce the number of hydroxyl groups in hemicelluloses and cellulose, reducing the hydrophilicity of bamboo

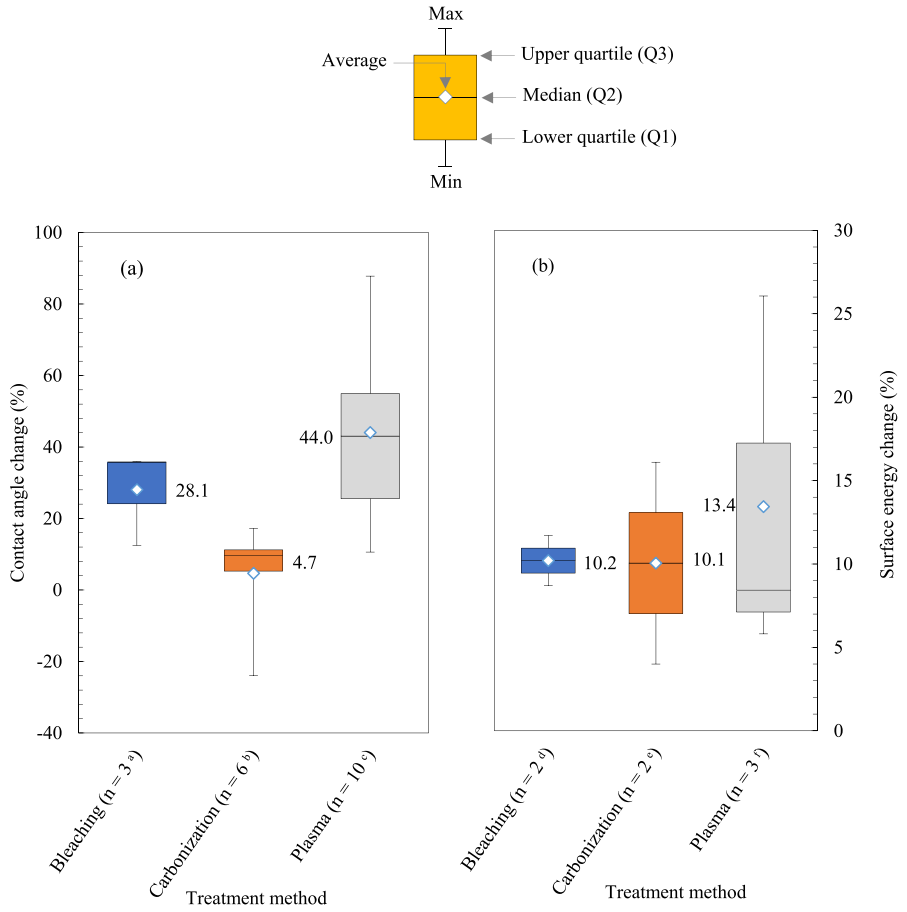


Fig. 9. Effect of chemical and physical treatments on bamboo wettability from published papers: (a) contact angle and (b) surface energy. *n*: number of data points. [a]: Ma [78], Zhang et al. [134], Shah et al. [113], [b]: Wang [135], Ma [78], Chen et al. [121], Guan et al. [128], Shah et al. [113], [c]: Hang et al. [127], Wu et al. [136], Li et al. [137], Rao et al. [130], Wang and Cheng [106], [d]: Ma [78], Shah et al. [113], [e]: Ma [78], Shah et al. [113], [f]: Wang [115], Zhou [138].

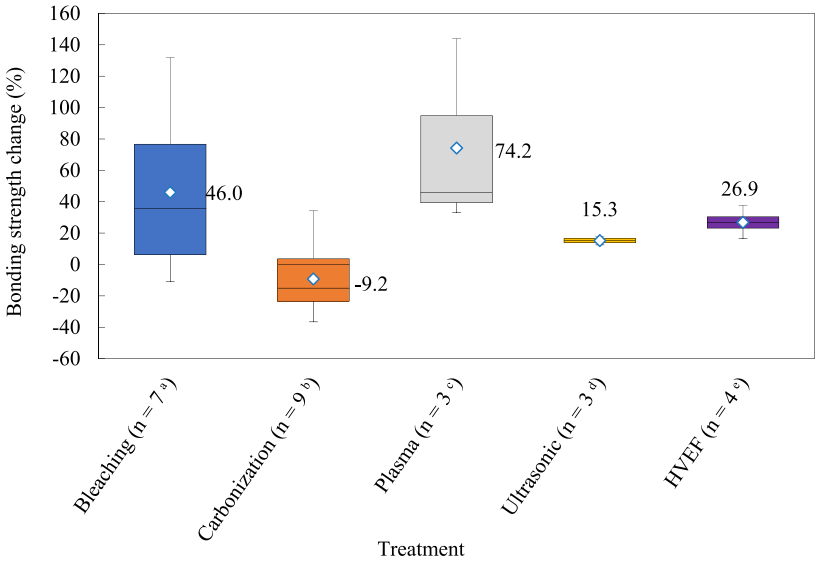


Fig. 10. Effect of chemical and physical treatments on bamboo bonding strength from literature. HVEF: high voltage electrostatic field and *n*: number of data points.
[a]: Zhang et al. [134], Shah et al. [113], [b]: Deng and Wu [120], Zhao et al. [139], Ma et al. [122], Shah et al. [113], [c]: Huang et al. [127],
[d]: Guan et al. [128], Yong et al. [132], [e]: He at al. [140], Ju et al. [141]. Adhesive used: soy-flour based adhesive, PVAc, PU, UF, PF, UPF, RPF.
PVAc: polyvinyl acetate, PU: polyurethane, UF: urea-formaldehyde, PF: phenol-formaldehyde, UPF: urea phenol-formaldehyde, RPF: resorcinol phenol-formaldehyde.

tissue. Chen et al. [121] found a 24% increase in the contact angle of Moso bamboo strip after carbonization, and a 23% decrease in bonding strength (PF adhesive), meaning a reduction in surface wettability with adverse effects on bonding. Bleaching in hot peroxide solution leaches out certain hydrophobic extractives like waxes and alters the pH and buffer capacity of bamboo elements that could affect bonding performance with water-based adhesives [107]. Plasma treatment generates physical and chemical changes in wood and bamboo surfaces (a few

nanometers to several hundred nanometers depth) when highly charged particles react with their chemical components, producing better penetration and interaction with PF adhesives [130]. Bamboo surface wettability by water-soluble adhesives like PFs is also influenced by other factors such as surface roughness and moisture content [142], as they strongly affect adhesive spread and penetration, and therefore bonding performance.

3.4. Bonding performance of engineered bamboo

3.4.1. Effect of treatments

The bond strength data from the literature shown in Fig. 10 demonstrate the correlation between surface characteristics and bonding performance. The higher increase in bonding strength after bleaching and plasma treatments is likely due to altered surface activation and/or pH and improved adhesive penetration into the modified bamboo pore network. Moreover, these findings suggest practical pathways to optimize bonding and promote bamboo utilization to manufacture sustainable engineered composites.

Carbonized bamboo showed minimal change in contact angle and surface energy (see Fig. 9a and b), which may help explain its adverse effect (−9.2%) on bonding strength. Several studies [55,143–145] demonstrate that temperatures above 180 °C significantly degrade hemicelluloses due to their highly branched and amorphous structure. Unlike hemicelluloses, cellulose is more thermally stable due to its higher molecular weight and crystallinity. According to Zuo et al. [144], cellulose in bamboo rapidly decomposes when temperatures reaches 200–250 °C, while lignin is completely degraded at temperatures between 250 and 400 °C. Therefore, the physical and mechanical properties of the bamboo tissue should not change significantly if carbonization temperatures are below 180 °C. However, Shao et al. [146] found that carbonization at 150 °C reduced bamboo tissue density by 7.8% accompanied by greater brittleness and decreased strength properties. The surface became harder and more difficult to bond.

Changes in surface acidity and buffer capacity after chemical treatments likely account for the variation in bonding strength of bamboo using phenolic adhesives. A study by Biswas et al. [107] reveals the following trend in pH and total buffer capacity (sum of acid buffer capacity and alkaline buffer capacity): carbonized bamboo < untreated bamboo < bleached bamboo. These findings indicate the importance of customizing bleaching and carbonization treatments based on the pH of the water-based phenolic resin used to manufacture bamboo composites.

3.4.2. Effect of adhesive type

Information from the literature points to certain wood adhesives being more suitable for bamboo than others. Table 6 shows the bonding strength of engineered bamboo products made with different adhesives from several studies. The vast majority of engineered bamboo composites are still made from PF resins as these are relatively inexpensive, durable and commercially available. PFs allow customization of viscosity and molecular weight distribution and co-addition of crosslinking agents and fillers in the mill setting. The resins can be applied and pressed in liquid, dried film or powder form and cured under well-defined conditions to obtain a strong, thermally stable, and moisture-proof bond [23].

In response to formaldehyde concerns, the bamboo products industry is pursuing alternatives to urea and phenolic resins [23]. Xing et al. [150] screened several wood adhesives for suitability to manufacture cross-laminated bamboo, including emulsion polymer isocyanate (EPI), polyurethane (PUR), melamine-urea-formaldehyde (MUF), hybrid polymer adhesive (HPA), and polyvinyl acetate (PVAc). Their study found that MUF performed best, and EPI was deemed unsuitable for bonding bamboo.

Isocyanate adhesives commonly used in the OSB industry for their efficacy at low doses and good thermal resistance. These adhesives have also been shown to be very suitable for strand-based bamboo composites [17,147,148]. They have been successfully adopted in industrial bamboo OSB manufacturing in China (CPC Yonglifa Forestry Co., Pers. Comm.). Based on historic market data trends pMDI is considerably more costly (1.5–2 times) than PF adhesives. It also requires more occupational health and safety (OHS) considerations as it is toxic in aerosol form, and machinery cleaning since it reacts with heat and moisture to harden and stick to metallic parts such as caul plates. pMDI is atomized into tiny discrete droplets using spinning disk atomizers onto smooth strand surfaces in a rotating drum tumble blender. The required dosage is lower (3–4%) than PFs (6%) for wood OSB and produces higher bonding strengths. The resin has good open time [151], requires lower curing temperature (90–109 °C) [34], and penetrates the S2 layer of the wood cell walls to produce 'spot-welds' between strands that act like nail bridges connecting to form a more robust structure at low resin dosages [152]. While interaction with wood species has been studied [153], the biuret penetration and curing chemistry of pMDI is still poorly understood in relation to the unique polylamellate structure of the bamboo cell wall.

On the other hand, pMDI may not suit all types of bamboo composites. In a study by Malanit et al. [17], relatively poor mechanical properties of bamboo-OSL of 0.75 g/cm^3 density resulted from using a high dosage of 10% pMDI. Both MOR and MOE were just 62.5 MPa and 10.50 GPa, respectively compared with BOSL of similar density (0.76–0.78 g/cm^3) made from 15% PF resin (MOR = 124.42 MPa, MOE = 15.45 GPa). There are no studies for bamboo using the PF-pMDI hybrid system [154,155] or other customized emulsion pMDI systems [156]. There are still many avenues for further research and understanding of how to adapt and customize chemical crosslinking resins to improve the poor resin efficiency currently used in the bamboo

Table 6
Bonding strength of various engineered bamboo products made with different types of adhesives.

Composite type	Element	Target density (g/cm^3)	Resin type	Resin target content	Pressing time	Test mode	Bonding strength (MPa)	Reference
OSB	Strands	0.70	MDI	5%	6 min	Tensile	0.53–0.71	Febrianto et al. [147]
		0.65		6%	10 min		0.22–0.48	Sumardi et al. [148]
OSL		0.75	MF	7–13%	12 s/mm		0.12–0.33	Malanit et al. [17]
			MUPF		16 s/mm		0.06–0.22	
			PF		12 s/mm		0.09–0.39	
			pMDI		10 s/mm		0.37–0.67	
LBL	Strips	0.74	Resorcinol	240–360 g/cm^2	6 min	Tensile	0.56–0.89	Nugroho and Ando [12]
		0.68	PUR	180 g/cm^2	4 h	Shear	16.00	Sharma et al. [27]
Scrimber	Bamboo bundles	1.15	PF	4–18%	30 min		8.92–21.57	Yu et al. [11]
		0.85–1.30		7–16%	30 min		6.10–16.90	Yu et al. [149]

OSB: oriented strand board, OSL: oriented strand lumber, LBL: laminated bamboo lumber. PF: phenol-formaldehyde, pMDI: polymeric methylene diphenyl diisocyanate, MDI: methylene diphenyl diisocyanate, MF: melamine-formaldehyde, MUF: melamine urea-formaldehyde, MUPF: melamine urea phenol-formaldehyde, PUR: polyurethane.

processing industry.

Further research is also needed to investigate and develop other non-phenolic chemical crosslinking resins such as soybean protein isolates potentially suitable for bonding various bamboo laminates. Semple et al. [157] tested a modified soybean protein isolate-based adhesive for bonding thermal-hydro-mechanical (THM) compressed Moso bamboo strips with dry bond strength between 2 and 4 MPa. Shah et al. [113] found that untreated and treated (bleached and carbonized) bamboo strips bonded with soy-based adhesive performed poorly in comparison to phenolic, polyurethane and polyvinyl acetate adhesives.

Finally, the use of cellulose nanofibrils/nanocrystalline cellulose to enhance PF, UF and PVAc resins have been investigated for wood composites [158,159] by improving resin viscosity and flow properties, bond strength and mechanical properties. Modified resins have successfully developed for improving wood composite processing in particleboard [160–162] and plywood [163–165]. Cellulose nanomaterials have excellent hydrogen bonding capacity with other cellulosic materials such as the wood cell wall [166]. They have also been shown to significantly improve the heat and moisture resistance of PVAc for structural applications [167]. Bamboo nanocellulose has been investigated to modify soybean-based resins [168], but few studies to date have been found on using cellulose nanofibril materials in resins for bamboo composites [169,170]. Evidence from wood bonding studies seems to suggest that these materials could play an important role in improving resin performance and efficiency in manufacturing bamboo or bamboo-wood composites. Of particular interest would be their possible application in improving the performance of PVAc and EPI resins for formaldehyde-free bamboo products.

3.4.3. *Effect of adhesive modification*

High MW and rigidity PF adhesives are less suitable for bonding bamboo without modification [44]. As demonstrated in Fig. 11, modified PF adhesives [24,42,44] are effective approaches to improving bamboo bonding strength. Anwar et al. [15] found improved moisture resistance (strength retention and bamboo failure) of three and five-ply bamboo boards made from bamboo strips pre-treated with low MW PF adhesive. Similarly, Huang et al. [44] found that using low and high MW PF in a dual adhesive system increased the shear strength of two-ply bamboo assemblies by 16%. According to the authors, the low MW resin applied first to bamboo strips penetrated bamboo cell walls, creating nanomechanical interlocking. The high MW resin applied to the PF-impregnated bamboo strips then filled the pores in the surface, creating higher bonding strength. Rao et al. [171] synthetized PF adhesives for bamboo scrimber composites and reported a MW of 542 and 2001 g/mol for low and high MW, respectively.

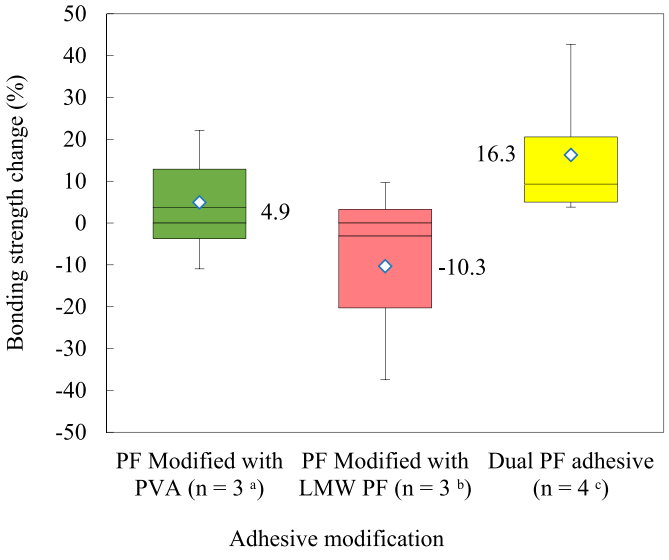


Fig. 11. Effect of adhesive modification on bamboo bonding strength from literature. *n*: number of data points. PF: phenol-formaldehyde, PVA: polyvinyl alcohol, LMW: low molecular weight.
[a] Guan et al. [42], [b] Guan et al. [24], [c] Huang et al. [44].

In another study, Guan et al. [24] found that PF modified with 10% low MW PF produced slightly higher dry bond shear strength than neat PF for two-ply bamboo assemblies but decreased the wet shear strength. This was thought to be caused by an expansion of bamboo cell walls due to an increased moisture content which disrupts hydrogen bonding between bamboo polymers and adhesive [172]. Modifying PF resins with plasticizing agents to improve their ductility for bamboo composites is effective. Guan et al. [42] tested the hypothesis that enhancing the ductility of PF resin with polyvinyl alcohol (PVA) could improve the shear strength of bonded bamboo. At 20% PVA addition, the bond strengths increased by 22%, and the high entanglement of PVA in the PF matrix produced a more ductile adhesive better able to absorb shear stresses. The dual PF adhesive system (low MW PF applied first followed by high MW PF) appears to be most effective and could be implemented in the bamboo composites industry to improve bonding performance.

4. Hybrid bamboo-wood composites

Numerous studies demonstrate the benefits of combining bamboo with wood (BW) to develop a wide range of higher-strength hybrid structural composites. Some examples of these products include BW-OSB [21,25,173], bamboo strip reinforced pine-OSL beams [174], BW-mat/curtain/veneer plywood container floors [175], BW-laminated veneer lumber (LVL) [28], bamboo strip and wood particle railway sleepers [176], BW-cross laminated timber (CLT) [26], and BW-glued laminated timber (glulam) [177].

Sinha and Clauson [177] fabricated five-layer BW-glulam using two layers (top and bottom faces) of laminated bamboo lumber (LBL) and three layers (core) of softwood (Douglas Fir). Substrate failure rate was 80% in the wood, followed by 12.5% in the adhesive phase and 5% in the bamboo, indicating the less dense wood phase was more prone to shear failure than the denser, stronger bamboo tissue and adhesive phase. This has implications for bond qualification testing, discussed in Section 5.

In another study, Chen et al. [28] investigated the feasibility of manufacturing a seven-layer BW-LVL using the following BW ratios: 71%B–29%W, 43%B–57%W, 29%B–71%W, and 57%B–43%W in different configurations (lay-up). As the relative proportion of bamboo increased, especially in the surface layers, the shear strength, MOR, and MOE of the composite increased indicating the positive effect of higher bamboo density and strength on the performance of the resulting BW hybrid composites.

While bamboos are more difficult to bond, its higher density does represent higher bond strength potential. In hybrid wood and bamboo strand composites, the presence of hard, difficult-to-compress bamboo tissue effectively transfers compaction stresses to the bondline and into any adjacent wood tissue producing greater deformation and contributing to stronger localized bond interfaces. For a given overall density product, higher density strands mean lower surface areas and hence greater resin coverage, regardless of bamboo or wood [178,179]. A study by Semple et al. [21] on three-layer OSB (0.75 g/cm^3 target density) made with PF resin showed similar IB strength for pure bamboo-OSB (0.77 MPa) and hybrid bamboo/wood-OSB (0.73 MPa). Interestingly, both were significantly higher than the pure wood-OSB (0.65 MPa) made under the same conditions. The moisture resistance (thickness swell) of bamboo-OSB was also improved.

Combining bamboo with wood also takes advantage of wood's greater specific stiffness, especially softwoods such as Douglas fir. Evidence from this review suggests the bamboo-wood interface has often been shown to be stronger and more functional than the bamboo-bamboo or the wood-wood interface, suggesting engineered

composites should maximize the occurrence of these interfaces in the lay-up. This is obviously easier for large element laminated composites than small element strand- and particleboards. Furthermore, the dual-phase PF system whereby the bamboo surfaces are pre-treated with low MW PF then hot pressed to wood strips or veneers coated with standard high MW PF plywood resin may be an industrially applicable method that can optimize the strength of the bamboo-wood bond interface. To the author's best knowledge, no studies have been found to date investigating this.

Bamboo's greater hardness and wear resistance has led to its successful development and use as surface material in mat and strand-based panels used in concrete formwork and shipping container flooring suitable for humid conditions [23,25,104]. Most solid hybrid composites locate the bamboo in the outer layers for its higher tensile strength. Indeed, structural building products commercialized today using bamboo are in combination with a wood core. For example, a Trade-marked laminated wall panel system made from South American timber bamboo surface strips and Douglas fir wood veneer core has been used and energy performance tested in passive homes and buildings in the US [180].

Finally, combining bamboo with wood can potentially lead to more effective utilization of wood resources to address dwindling global timber supplies [25,102]. Wood-wood composites have been proven in both light frame and heavy timber construction at least in Western countries, and therefore do not require further improvement and the inclusion of bamboo. The philosophy around adopting bamboo could be considered as '*how can a wood-bamboo composite be designed and fabricated to be just as reliable or more than its pure wood analogue and used for timber frame construction in countries where wood has become scarce and cheaper, faster growing bamboo is plentiful*". A corollary to this is whether adhesives customized to better suit bamboo are reversable back to the wood adherend, i.e., are they still as optimal for wood surface bonding as the original unmodified resin. This question warrants further investigation as the commercialization and application of hybrid wood-bamboo composite building materials increases in future.

5. Testing methods to evaluate the performance of bamboo bonding

Various researchers have tested bamboo composites using standard testing methods for wood composites depending on which they most closely resemble, as shown in Table 7. Testing methods for wood composites that are applicable for some bamboo composites include (a) ASTM D1037 [181]; for bond evaluation of bamboo fiber and strand-based composites, (b) ASTM D143 [182], ASTM D2344 [183], and ASTM D905 [184]; for bond shear evaluation of bamboo veneer-based composites, bamboo scrimber and glued laminated bamboo, respectively, and (c) ASTM D5456 [185]; for accelerated bond aging and durability assessment of bamboo strand and veneer-based composites as well as bamboo scrimber.

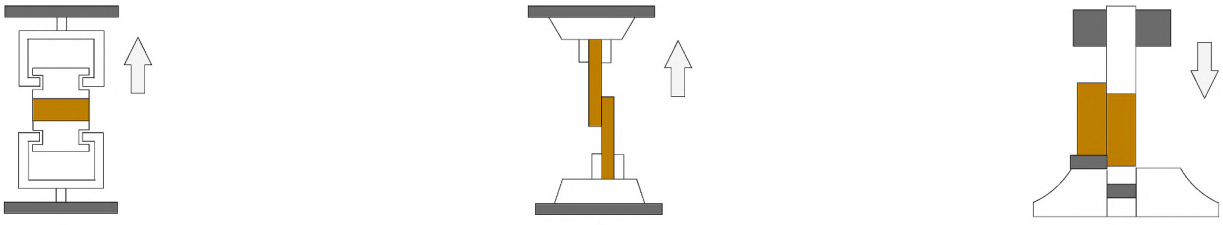
Xing et al. [150] tested a range of adhesives on bamboo, concluding that standard test methods for evaluating bond shear strength in wood CLT could be applicable for testing bamboo CLT. However, other testing protocols and bond qualification criteria including CSA-O151 [191] and NIST PS-2 [192] for plywood, JAS SIS-24 [193] and APA PRL-501 [194] for LVL, and ANSI/APA PRG-320 [195] for mass timber products may require further consideration regarding bond moisture durability testing bamboo or wood-bamboo hybrid composites.

As discussed earlier, unique features of bamboo culm tissue compared to wood create challenges for bonding surfaces with commercial wood adhesives. Therefore, using wood composites testing methods and bond qualification criteria for bamboo composites may result in an inaccurate assessment of composite adequacy. For instance, ANSI/APA PRG-320 protocols for evaluating bond durability in mass timber products use a cross-laminated three-layer sandwich glued assembly of 1.25 inches (31.75 mm) thick lumber pieces subjected to a vacuum-pressure-dry procedure to stress the bond lines based on the swelling/shrinkage characteristics of reference softwoods (Douglas fir or Lodgepole pine). Achieving this thickness of solid bamboo substrate without adhesive lines is physically impossible. The applicability of the PRG-320 bond qualification methodology may also be affected by bamboo's different density and shrinkage/swelling behavior compared with the woods stipulated in PRG 320.

Another difference is that bond qualification criteria for wood composites based on high (80%) wood failure, such as NIST PS-2 and CSA O151, rely on low wood shear strength characteristics relative to the adhesive phase. The lack of PF adhesive penetration into bamboo cells (see Fig. 6a and b) and the high strength of bamboo tissue mean that the percentage of tissue failure rate may be considerably lower in a bond shear test made on a multi-layer bamboo composite compared with wood using the same resin, even if the recorded strength is high. However, this bond qualification criterion may still be relevant to bamboo-wood bonds, particularly if stress transfer by the bond is sufficient to cause 80% or greater failure area in the wood adherend. Unlike

Table 7
Testing methods for bamboo bonding from published papers.

Bondline type	Testing type	Test schematic	Composite type	Standard	Reference
Discontinuous	Internal bond	a	BOSB	ASTM D1037[a]	Semple et al. [21]
				JIS A 5908 [b]	Sumardi et al. [148]
			BOSL	EN 300[c]	Malanit et al. [17]
Continuous	Lap shear	b	Ply bamboo	BS EN 314-1 [d]	Anwar et al. [15]
					Semple et al. [157]
				ASTM D3163[e]	Shah et al. [113]
	Shear block	c	Scrimber	ASTM D2344[f]	Yu et al. [11]
					Yu et al. [149]
			GLB	ASTM D905[g]	Sinha et al. [186]
			CLB	EN 392 [h]	Xing et al. [150]



a b c

BOSB: bamboo-oriented strand board, BOSL: bamboo-oriented strand lumber, GLB: glued laminated bamboo, CLB: cross-laminated bamboo. [a]: ASTM [181], [b]: JIS [187], [c]: EN [188](1997), [d]: BS (2004), [e]: ASTM [189], [f]: ASTM [183], [g]: ASTM [184], [h]: EN [190].

structural wood composites, there are currently no internationally recognized standards for bond qualification testing in bamboo or wood-bamboo composite building materials, and further fundamental research is required to develop these.

6. Research challenges and outlook

This review discussed a wide variety of adhesive-bonded bamboo and bamboo-wood hybrid composites developed in recent years, mainly produced for the flooring, decking, and structural composite lumber market. Key challenges include improving material recovery from culms and ameliorating the adverse effects of very low bamboo permeability and porosity, as well as the inhibitory inner pith and outer cortex layers.

Several laboratory and industrial treatment processes and adhesive modifications have been tested on bamboo with varying degrees of success at increasing the bond performance. Many of today's laminated and scrimber-based bamboo processing methods are inefficient, relying on a high degree of culm wall damage and therefore high adhesive consumption compared with wood composites. Higher adhesive consumption is also necessitated by the strict upper size limit on bamboo elements (high surface area to volume ratio) compared with laminated wood such as glulam and CLT.

Maximum-recovery elements such as some flattened culm products and esterilla where the inner pith and outer cortex remain create further problems for adhesive bonding as these layers are hard, waxy, and impervious to wetting. The heterogeneity and rough/fissured surface of some high-recovery bamboo elements such as flattened bamboo bundles, esterilla and broomed culm strips lead to excessive adhesive consumption and required compaction. These increase energy and production costs and can sacrifice strength properties relative to density and material input, especially when compared with the manufacturing efficiencies of engineered wood composites. Techniques such as flattening culms without splits and cracks [103,196,197] and sandblasting (micro removal) of the cortex [198,199] have also been developed. Strategies that radially slice culm wall sections to isolate the cortex to a thin edge and away from the element surface [100,101,199] are recommended for processing curtain-sliver composites or strand-based composites, making bamboo OSB a commercially viable venture, particularly for shipping container flooring.

Over the last decade, the significant growth in research and industrial development of bamboo-wood hybrid composites has led to commercialized building products. These capitalize on the relative material density, strength and stiffness advantages of these two complementary materials and the higher bond interface strength between wood and bamboo compared with pure bamboo. A better fundamental understanding of the bamboo-wood bond interface will further improve product design and manufacturing processes, optimize adhesives for BW hybrid composites, and possibly lead to revised standards for bond qualification in these products. Product design parameters like BW ratio, element characteristics (i.e., geometry, size, surface preparation/treatment, wettability), configuration and orientation, and process parameters including resin formulation, mat lay-up and cold/hot compression play a critical role in product properties and performance. Approaches to address these challenges include further investigation of MW customization of PF adhesives for bamboo, bamboo pre-treatment with low MW PF before gluing to wood, and applying computer simulation and statistical models already developed and successfully used for engineered wood composites.

Focus areas for future bamboo composite research should be: 1) maximize recovery and enhance quality and uniformity of bamboo elements (such as radially sliced strips, veneers, broomed mats and flattened culms), 2) facilitate the transition to high volume, automated processing of elements and composites, similar in manner to engineered wood products, 3) reduce reliance on chemical-intensive treatments for elements or find ways of recovering and recycling chemicals, 4) further develop bamboo pre-treatments and formaldehyde-free adhesives including lower dose chemical crosslinking adhesives such as pMDI and natural protein-based formulations for bamboo composites, 5) further develop bamboo-wood hybrid composites for better bonding performance, customization of flexural moduli (MOE and MOR), and reduction in overall product density, and 6) develop standards for bond qualification testing of bamboo-wood composites, adapted from those used for wood composites. A better understanding of the interactions between material type (bamboo or wood) and element preparation, adhesive type, and application methods are needed. One of the most potentially promising and under-studied areas is converting smooth radial strand elements that confine cortex to one thin edge and leveraging the automated conversion, resin application, mat lay-up, and hot-pressing technologies of the wood-OSB and OSL industries. These are developed to successfully use low-dose, high-strength 'spot-weld' adhesives such as pMDI to help boost resin efficiency, output, and formaldehyde emissions. Strand technology also allows for a high degree of product design optimization, process automation, control, and efficiency, currently not a feature of the bamboo processing industry.

This review demonstrates the importance of better understanding bamboo bonding to improve the performance of bamboo and bamboo-wood composites and promote their utilization in timber-frame infrastructure as shown in Fig. 1a and b. Most advances in adhesion science and technology for wood-based composites can be applied to bamboo and bamboo-wood composites. For instance, exterior-grade wood adhesives such as PF are used for bamboo structural panels, including scrimber, strand, and veneer-based products. Another highlight from the review is that building code approval and application of bamboo and bamboo-wood composites in wood-frame construction is currently limited by the lack of agreed standards and protocols for accurate bond durability assessment.

7. Summary and conclusions

In this paper, fundamental and practical aspects of bamboo adhesion in bamboo-based composites manufacturing were critically reviewed to facilitate better understanding of the greater challenges associated with bonding bamboo compared with wood. Innovative approaches beyond existing industrial methods to improve bonding performance of bamboo composite products were discussed. The key conclusions are the following:

1. Compared with wood, bamboo is high in density and high in starch, wax and silica content. In addition, chemical and microstructural gradients across the bamboo culm wall create challenges for bonding with adhesives formulated for wood.
2. Micro-scale adhesive penetration into bamboo is hampered by its low porosity and low cellular connectivity, as well as sub-optimal wood adhesive attributes such as viscosity, molecular weight (MW) distribution, and solids content. Adhesive penetration on the nanometer level into the bamboo cell wall by low MW phenol-formaldehyde (PF) and polymeric methylene diphenyl diisocyanate (pMDI) remains poorly studied compared with wood.
3. Wettability and penetration of bamboo can be significantly improved after industrial bleaching and experimental plasma treatments, both leading to improvement in bonding.
4. PF adhesives are currently most commonly used in the bamboo composite industry. Modification of rigid PF adhesives with low MW PF and/or with more ductile polymers such as polyvinyl alcohol (PVA) has been shown to improve bonding performance of bamboo. A dual phase system of low MW PF application to bamboo followed by bonding with high MW PF appears most effective for bamboo and mixed bamboo-wood bonding.
5. Similar to wood OSB, pMDI adhesives are also shown to be suitable for bamboo strand-based composites and have good potential for formaldehyde-free production. However, emulsion polymer

isocyanate (EPI) and polyurethane (PUR) appear less suitable for bamboo bonding and require further development.
6. Bamboo is best combined with wood to improve resin efficiency and interfacial bond quality, reduce composite weight, and improve certain properties such as shear and specific stiffness compared with pure bamboo.
7. Higher recovery, bondable bamboo elements have been developed for veneer composites by culm softening and flattening technology where the non-bondable cortex layers are removed or modified through abrasion or 'fiberization'. Other recovery and bonding optimization potentials lie in radially cut thin strip and strand composites that confine the cortex and pith to a thin edge of the element away from the bond interface. Such products can have high recovery and require lower doses of adhesive.
8. Further developments in the design and manufacture of conversion machinery to produce consistent quality bamboo elements, customizing bamboo adhesives, and modeling mat-forming and pressing processes for bamboo composites are needed.
9. The adaptation of engineered wood product standards for bonding evaluation of bamboo and bamboo-wood composite building materials is also required.

Author contributions

W. N. Nkeuwa: Investigation, Writing-Original Draft, Writing-Review and Editing.

J. Zhang: Investigation, Writing - Original Draft, Data curation and Software.

K. Semple: Investigation, Writing - Original Draft, Writing-Review and Editing.

M. Chen: Investigation, Writing - Original Draft, Review and Software.

Y. Xia: Investigation and Data curation.

C. Dai: Funding Acquisition, Conceptualization and editing, Supervision, Project Administration.

Declaration of competing interest

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

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