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Effect of Steam-Treatment Duration on the Physical and Mechanical Properties of Three-Layer Betung Bamboo (*Dendrocalamus asper*) Plybamboo Board

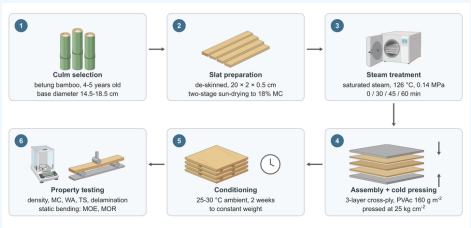
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ABSTRACT



Betung bamboo (*Dendrocalamus asper*) is a fast-growing, carbon-storing lignocellulosic resource that can relieve harvesting pressure on tropical hardwood, but its high starch and extractive content impairs adhesion and weakens bonded bamboo panels. Steam treatment offers a solvent- and chemical-free route to degrade these components, yet the exposure time best suited to a three-layer, poly(vinyl acetate) (PVAc)-bonded plybamboo board (PBB) has not been established for this sheet-based, cross-laminated architecture. We manufactured cross-laminated PBB (30×30×1.5 cm) from betung slats steamed with saturated steam at 126 °C for 0, 30, 45, and 60 min and measured density, moisture content, water absorption, thickness swelling, delamination, and static bending properties parallel and perpendicular to the grain. A short 30 min treatment gave the best mechanical profile, raising density by 11%, lowering water absorption by 19% and thickness swelling by 42%, and increasing parallel-grain modulus of elasticity and rupture by 82% and 56% relative to the untreated control; perpendicular-grain bending was statistically unchanged. The stiffness gain persists after density normalisation: the density-normalised (specific) modulus rose 64%, and panel density explained only 40% of the cross-panel variance in modulus. Longer treatment continued to improve dimensional stability (thickness swelling down 65% at 60 min, significantly below the 30 min value, and delamination down 54%) but progressively lowered density and strength. Measured moisture contents were below the SNI 8032:2014 reference limit (≤14%), and parallel-grain bending strengths exceeded the SNI 01-5008.7-1999 reference value, but none reached the intended 0.7 g cm^{-3} target density, and modulus of elasticity and perpendicular-grain strength fell short of the structural thresholds. Within this green, water-only process panel densification and adhesive formulation and application warrant further investigation, indicating where future optimisation of sustainable plybamboo should be directed.

Keywords: *Sustainable Materials; Betung Bamboo (Dendrocalamus asper); Steam Treatment; Plybamboo Board; Dimensional Stability; Green Building Materials*

1. INTRODUCTION

The transition to a low-carbon, circular built environment is driving demand for structural and non-structural panels made from rapidly renewable feedstocks rather than slow-growing tropical hardwood. Bamboo is among the most attractive of these feedstocks: it reaches harvestable maturity in three to five years, regenerates from existing rhizomes without replanting, and stores carbon while relieving logging pressure on natural forests [1,2]. Indonesia hosts a particularly rich bamboo flora, in which the genus Dendrocalamus is widely distributed [3,4,5], and betung bamboo (*Dendrocalamus asper*) stands out for mechanical properties comparable to those of local structural timbers [6,7]. Converting culms into engineered panels is therefore a route to sustainable, locally sourced building materials.

Plybamboo board (PBB), formed by bonding several sheets of bamboo slats in alternating grain orientation, is one such product. Its physical and mechanical behaviour depends on the bamboo species, the anatomy of the culm, and the compatibility between the substrate and the adhesive [8,9]. A persistent obstacle is the high content of starch, sugars, and other extractives in bamboo, which are hydrophilic, poorly wettable, and chemically inert toward common wood adhesives; they hinder resin penetration, weaken the bond line, and leave panels prone to moisture uptake and swelling [10,11,12].

Modifying the substrate to remove or degrade these extractives is thus central to making durable bamboo panels. Among the available options, saturated-steam treatment is the most compatible with green-manufacturing goals: it uses only water and heat, introduces no solvents, halogenated reagents, or formaldehyde-based chemicals, generates no liquid chemical effluent, and is readily scaled with standard autoclave equipment. Under moist heat, hemicellulose is progressively hydrolysed and hygroscopic extractives are degraded, which improves wettability and dimensional stability [13,14,15,16,17,18]. The same chemistry, however, carries a trade-off: prolonged exposure depolymerises load-bearing hemicellulose and can reduce strength [19,20,21]. The useful treatment window is therefore a balance between extractive

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removal and matrix preservation. Pairing steam treatment with a water-based, formaldehyde-free PVAc adhesive keeps the whole process within a low-emission framework.

This time–temperature balance has been studied most thoroughly for bamboo-oriented strand board (BOSB), where steaming betung strands at 120 °C to 130 °C improves adhesion and panel properties [13,14,22,23,24,25]. Sheet-based, cross-laminated plybamboo, however, is a distinct architecture: it is built from continuous slats rather than dispersed strands, its bond lines are continuous, and its response to soaking and bending is governed by whole-sheet cross-ply behaviour rather than by a randomly oriented mat. Whether the short steaming windows optimal for strand boards transfer to sheet-based PBB has not been resolved.

We therefore set out to identify the steam-treatment duration (30, 45, or 60 min at 126 °C) that best suits betung slats used in three-layer, PVAc-bonded plybamboo board, and to compare moisture content with SNI 8032:2014 and mechanical properties with the thickness-matched values in SNI 01-5008.7-1999 for 15-mm structural plywood. These wood-plywood values serve as reference benchmarks for the bamboo panels, rather than as evidence of product certification. We hypothesised that a short steaming window would improve dimensional stability and bond quality without the strength penalty of prolonged exposure, and that identifying this window would reveal whether panel densification and adhesive selection, rather than further substrate modification, are the factors limiting commercial-grade betung plybamboo.

2. MATERIALS AND METHODS

The overall experimental workflow — raw-culm selection, slat preparation, steam treatment, three-layer panel assembly, pressing, conditioning, and the physical and mechanical characterisation of the finished board — is summarised in Fig. 1. Unless stated otherwise, conditioning and testing were carried out under ambient laboratory conditions of 25 °C to 30 °C. Relative humidity was ambient and was not controlled; numerical RH measurements for conditioning and testing were not available.

2.1 Raw Materials

Culms of betung bamboo (*Dendrocalamus asper* (Schult. f.) Backer ex K. Heyne), four to five years old and 14.5 cm to 18.5 cm in external base diameter, were obtained from a managed stand in Sukadana, East Lampung, Indonesia. Culm age was taken from the grower's harvest records and confirmed visually from the loss of the culm sheath and the development of lichen on the outer surface. Only straight, mature culms free of visible insect attack, fungal discoloration, splits, and mechanical damage were selected. After felling, culms were stored under ventilated shade to prevent case-hardening and mould before processing. The panel adhesive was Crona 234 SR, a ready-to-use, cold-setting, water-based poly(vinyl acetate) (PVAc) emulsion for interior laminating, used as supplied without dilution, hardener, or extender. Principal apparatus comprised a saturated-steam laboratory autoclave, a forced-convection oven, an analytical balance (0.01 g), a silica-gel desiccator, a digital caliper and micrometer (0.01 mm), and a universal testing machine (Zwick/Roell 7250, type 8803).

2.2 Preparation of Bamboo Slats

Culms were cross-cut into internode segments and split longitudinally into strips. Both surface layers — the waxy, silica-rich outer skin (exodermis) and the softer inner skin (endodermis) — were removed because they are poorly wettable and impair bonding. The de-skinned strips were planed to slats of 20 × 2 × 0.5 cm (length × width × thickness) with the fibres running along the long edge. Drying was in two stages: the slats were sun-dried until a distinct colour change indicated loss of free water, then sun-dried again until the moisture content reached about 18%, checked periodically by the oven-dry method on sacrificial samples. Warped, checked, or defective slats were discarded, and the remainder were sorted by thickness so that each panel was built from closely matched slats.

2.3 Steam Treatment

The conditioned slats were divided into an untreated control and three steam-treated groups. Each treated group was exposed in the autoclave to saturated steam at 126 °C and a gauge pressure of 0.14 MPa for 30, 45, or 60 min. Timing began once the chamber reached the 126 °C set point, so the reported durations correspond to effective time at temperature. The chamber was then depressurised slowly and the slats cooled. The temperature, pressure, and duration window follows the betung strand-modification protocol of Maulana et al. [22]. To remove moisture as a confounding variable, all groups — treated and control — were air-dried for about one week and then oven-dried at 60 °C to 80 °C for three days to below 5% moisture content, providing the dry substrate favoured by cold-setting PVAc.

2.4 Manufacture of Three-Layer Plybamboo Board

Three-layer, cross-laminated panels of nominal size 30 × 30 × 1.5 cm and a target density of 0.7 g cm^{-3} were manufactured with the core-layer grain perpendicular to that of the face and back layers, giving a balanced cross-ply construction. The number of slats per layer was set so that each layer formed a continuous, gap-free sheet. PVAc adhesive was applied at 160 g m^{-2} by the single-spread method, meaning that only one of the two mating surfaces at each interlayer bond line was coated. The assembly was cold-pressed at 2.45 MPa (25 kg cm^{-2}) for 24 h at ambient temperature until the bond set. The de-skinned, planed slats provided the intended contact surfaces. During pressing, adhesive transfer to the uncoated mating surface can occur; the adequacy of this transfer depends on surface condition, adhesive flow, assembly time, and pressure [26]. This provides a rationale for single spreading, but does not demonstrate uniform wetting at the applied spread rate. Adhesive coverage and penetration were not quantified, and no comparison with double spreading was made. Panels were edge-trimmed and conditioned for two weeks at 25 °C to 30 °C under ambient laboratory humidity to constant weight, then cut into test specimens and re-conditioned under the same ambient conditions before testing. Three panels were manufactured independently per treatment, giving twelve panels in total. For each measured property, one test specimen was obtained from each replicate panel, giving three independent panel-derived observations per treatment. Specimens for different tests were separate pieces cut from the same replicate panel; density and moisture content, in particular, were determined on separate specimens. MOE and MOR in a given direction were obtained from the corresponding bending test.

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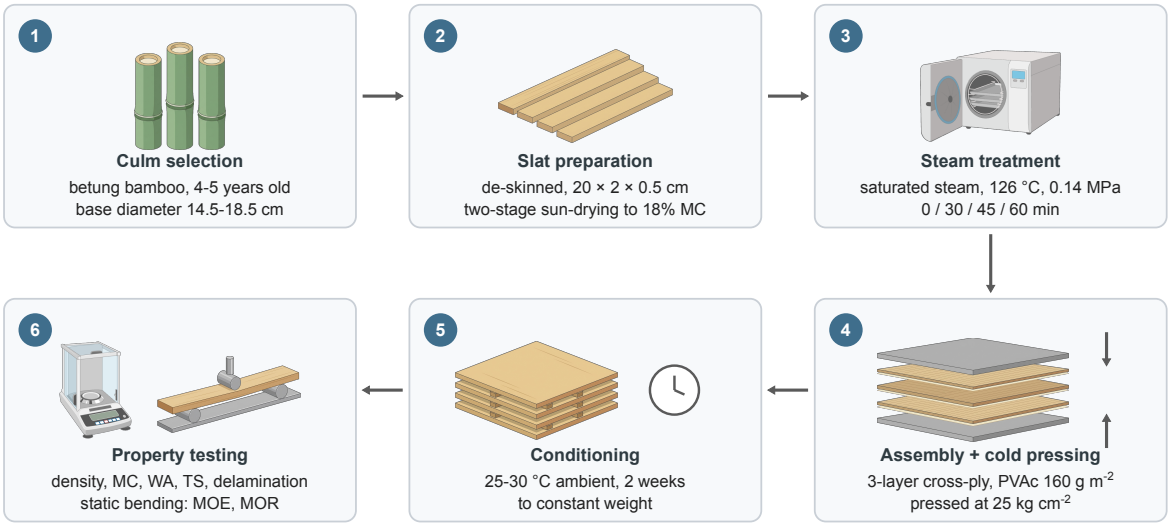


Figure 1. Experimental workflow from raw betung culm to the physical and mechanical characterisation of the three-layer plybamboo board.

2.5 Determination of Physical Properties

Physical-property specimens were prepared following ASTM D143-05 [27]. Moisture content and bond quality were evaluated with reference to the Indonesian plywood standard SNI 8032:2014 [28]; because that standard sets no minimum board density, density is reported against the 0.7 g cm^{-3} manufacturing target.

2.5.1 Density and Moisture Content

Density and moisture content were measured on separate 10 × 10 × 1.5 cm specimens from each replicate panel. Mass was recorded on the analytical balance and volume computed from averaged caliper measurements. Specimens were oven-dried at 103(2) °C to constant weight (≥24 h), cooled in a desiccator for 15 min, and reweighed:

$$\mathrm{MC}\,(\%) = \frac{B_a - B_k}{B_k} \times 100, \tag{1}$$

$$\rho = \frac{m}{V}, \tag{2}$$

where B_a and B_k are the air-dry and oven-dry masses, m is the specimen mass, and V its volume. Under SNI 8032:2014 a plywood specimen is satisfactory when its mean moisture content does not exceed 14%.

2.5.2 Water Absorption and Thickness Swelling

Water absorption (WA) and thickness swelling (TS) were measured on 5×5×1.5 cm specimens submerged in distilled water at room temperature for 24 h:

$$\mathrm{WA}\,(\%) = \frac{W_2 - W_1}{W_1} \times 100, \tag{3}$$

$$\mathrm{TS}\,(\%) = \frac{T_2 - T_1}{T_1} \times 100, \tag{4}$$

where W_1, W_2 and T_1, T_2 are the mass and thickness before and after soaking. Neither SNI 8032:2014 nor SNI 01-5008.7-1999 sets a limit on WA or TS; both are reported as measures of dimensional stability.

2.5.3 Delamination

Bond durability was assessed by a soak–dry delamination test on 5 × 5 × 1.5 cm specimens, with one specimen from each independently manufactured panel. The reported exposure sequence consisted of immersion in water for 6 h followed by oven-drying at 40 °C for 18 h, adapted from the soaking-delamination procedure of the Japanese glued-laminated-timber standard JAS 234 [29]. The number of consecutive soak–dry cycles could not be verified from the available study documentation. The delamination results are therefore reported as a comparative index with an incompletely documented exposure history, rather than as a fully reproducible durability classification. The total length of open bond line along the specimen edges was summed:

$$\text{Delamination}\,(\%) = \frac{L_d}{L_t} \times 100, \tag{5}$$

where L_d is the separated bond-line length and L_t the total bond-line length. SNI 8032:2014 judges bond quality from tensile-shear bond strength and the percentage of wood failure rather than from a delamination ratio, so the values reported here have no direct numerical equivalent in the standard and are used as a relative measure of bond durability among treatments.

2.6 Determination of Mechanical Properties

Modulus of elasticity (MOE) and modulus of rupture (MOR) were determined by three-point static bending on the universal testing machine using 20 × 5 × 1.5 cm specimens, tested both parallel and perpendicular to the grain of the face layers to capture the anisotropy of the cross-ply panel. Each specimen was simply supported over a span of 15 cm (span-to-depth ratio of 10) and centrally loaded to failure at a crosshead speed of 10 mm min^{-1} :

$$\mathrm{MOE} = \frac{\Delta P\, L^3}{4 b\, h^3\, \Delta y}, \tag{6}$$

$$\mathrm{MOR} = \frac{3 P_{\max} L}{2 b\, h^2}, \tag{7}$$

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where $\Delta P/\Delta y$ is the slope of the linear region of the load–deflection curve, P_{max} the maximum load, L the support span, b the width, and h the depth. Because SNI 8032:2014 prescribes no minimum bending properties, MOE and MOR were benchmarked against the thickness-matched requirements of SNI 01-5008.7-1999 [30] for 15-mm plywood. This standard was selected as a comparative reference because the present three-layer panels share an alternating-grain, bonded-layer architecture with plywood, and their nominal 15-mm thickness permits a thickness-matched comparison. Nevertheless, bamboo slats differ from wood veneers in anatomy, geometry, and bond-line characteristics. The comparison therefore does not establish formal compliance with the wood-plywood standard or suitability for structural use.

Three derived quantities were computed for each replicate panel: specific parallel-grain stiffness ($MOE_{\parallel}/\rho$), specific parallel-grain strength ($MOR_{\parallel}/\rho$), and the stiffness anisotropy ratio ($MOE_{\parallel}/MOE_{\perp}$). The parallel-grain bending result was paired with the density measured on a separate specimen from the same identified panel, rather than with the treatment-average density or a specimen from another panel. The anisotropy ratio likewise paired the parallel- and perpendicular-grain bending results from that same panel. Each treatment thus contributed three panel-specific ratios. $MOE_{\parallel}$ and $MOR_{\parallel}$ were also regressed on the corresponding panel densities across all twelve panels, with treatments pooled, by ordinary least squares. This pairing assumes that the separate density specimen adequately represents the associated panel; it does not measure the local density of the bending specimen itself.

2.7 Experimental Design and Statistical Analysis

The experiment followed a completely randomised design with steam-treatment duration as the single factor at four levels (control/0, 30, 45, and 60 min) and three replicate panels per level. The independently manufactured panel was the experimental unit. For each property, one specimen from each panel supplied one observation, so the ANOVA used three observations per treatment and twelve observations overall, without pooling multiple specimens as independent replicates. Because there was only one specimen per panel for each property, its value was also that panel's value for the analysis; no average of multiple within-panel specimens was needed. These panel-derived observations were subjected to one-way analysis of variance (ANOVA); normality of the residuals (Shapiro–Wilk) and homogeneity of variance (Levene's test on medians) were verified beforehand and satisfied for every property ($p > 0.05$). Exact F and p values are reported together with the effect size η^2. Where the treatment effect was significant ($p < 0.05$), means were separated by Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$. Results are reported as mean ± standard deviation (n = 3); means labelled with different lowercase letters differ significantly, letters ascend with the group mean, and "n.s." denotes no significant difference among treatments. Mechanical properties were converted from the as-measured kg cm^{-2} to SI units using 1 kg cm^{-2} = 0.0980665 MPa.

3. RESULTS AND DISCUSSION

3.1 Physical Properties

The density, moisture content, water absorption, thickness swelling, and delamination of all four treatments are collected in Table 1 and shown in Fig. 2.

3.1.1 Density and Moisture Content

Steam treatment significantly changed panel density ($F(3, 8) = 35.2$, $p < 0.001$, $\eta^2 = 0.93$). Density rose from 0.53 g cm^{-3} in the control to 0.59 g cm^{-3} at 30 min (0.58 g cm^{-3} at 45 min; the 30- and 45 min values share a statistical group and are not distinguishable), then fell sharply to 0.45 g cm^{-3} at 60 min. The early gain is consistent with degradation of hygroscopic extractives, which improves resin penetration and consolidates the bond line, as reported for betung strands under this exact steaming protocol [14,22]; the steep decline at 60 min reflects hemicellulose depolymerisation and mass loss that lower the substrate density faster than compaction can compensate. The compositional direction of both effects is well established for saturated steam: hemicellulose content falls while the relative cellulose and lignin fractions rise [17]. Notably, no treatment reached the 0.7 g cm^{-3} manufacturing target (all fell between 0.45 and 0.59 g cm^{-3}), pointing to incomplete compaction during cold pressing as a process limitation independent of steaming. Moisture content stayed within a narrow 10.74–11.10% band and was not significantly affected by duration ($F(3, 8) = 2.85$, $p = 0.105$). Every board met the SNI 8032:2014 moisture-content limit of ≤14%.

3.1.2 Water Absorption and Thickness Swelling

Steaming significantly lowered both WA ($F(3, 8) = 15.2$, $p = 0.001$) and TS ($F(3, 8) = 59.9$, $p < 0.001$) relative to the control, and, unlike density, both kept improving as duration increased. WA fell from 50.4% in the control to 41.0% at 30 min and 35.7% at 60 min (a 29% reduction), although the three steamed groups were not statistically separable. TS dropped from 9.1% to 5.3% at 30 min and 3.2% at 60 min, a 65% reduction; here the gain with longer steaming is itself significant, the 60-min boards swelling less than the 30-min boards (Table 1). This monotonic gain is consistent with steam-induced hydrolysis of hemicellulose and the loss of accessible hydroxyl groups, which reduces the material's capacity to bind and exchange water [17,18]. Dimensional stability is thus the one property family that rewards the longest treatment tested.

3.1.3 Delamination

Delamination differed significantly among treatments ($F(3, 8) = 15.6$, $p = 0.001$) and tracked the improvement in dimensional stability: it fell from 32.4% in the control to 22.6% at 30 min, 16.0% at 45 min, and 15.0% at 60 min. The three steam-treated groups share a statistical group, so the largest, robust step is from the untreated control to any steamed board. As noted in Section 2.5.3, SNI 8032:2014 evaluates bond quality by tensile-shear strength and wood failure rather than by a delamination ratio; the delamination reported here is therefore a relative index, and its persistence at 15–23% indicates that substantial open bond line remains even in the best case.

3.2 Mechanical Properties

The MOE and MOR of all treatments, parallel and perpendicular to the grain, are given in Table 2 and Figs. 3–4.

3.2.1 Modulus of Elasticity

Parallel-grain MOE was significantly affected by duration ($F(3, 8) = 10.8$, $p = 0.003$, $\eta^2 = 0.80$), climbing from 2.03 GPa in the control to a peak of 3.69 GPa at 30 min — an 82% increase — before easing to 2.66 GPa at 45 min and 2.15 GPa at 60 min; under Tukey's test the 45 min mean is intermediate, not separable from either the 30 min peak or the control and 60 min

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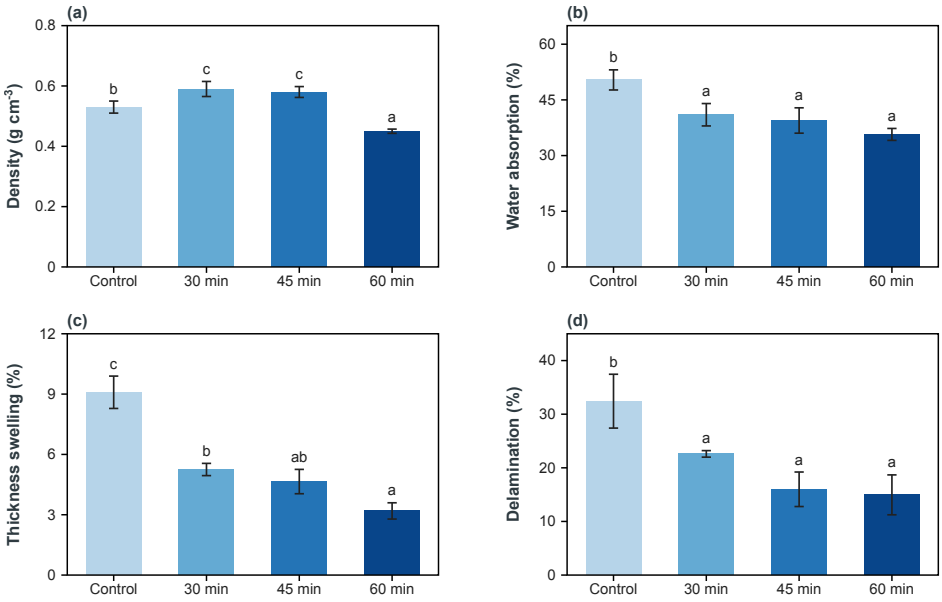


Figure 2. Physical properties of plybamboo board as affected by steam-treatment duration: (a) density, (b) water absorption, (c) thickness swelling, and (d) delamination. Bars are mean ± SD (n = 3 independent panels); different letters denote significant differences (Tukey's HSD test, $p < 0.05$); n.s. = not significant.

Table 1. Physical properties of three-layer plybamboo board by steam-treatment duration. Mean ± SD (n = 3 independent panels). Different lowercase letters within a row denote significant differences (Tukey's HSD test, $p < 0.05$), with letters ascending with the group mean; n.s. = not significant.

Property	Control (0 min)	30 min	45 min	60 min
Density (g cm^{-3})	0.53 ± 0.02^{b}	0.59 ± 0.03^{c}	0.58 ± 0.02^{c}	0.45 ± 0.01^{a}
Moisture content (%)	11.10 ± 0.16	10.88 ± 0.05	10.74 ± 0.16	10.90 ± 0.20 (n.s.)
Water absorption (%)	50.38 ± 2.71^{b}	41.00 ± 3.01^{a}	39.45 ± 3.42^{a}	35.70 ± 1.61^{a}
Thickness swelling (%)	9.09 ± 0.81^{c}	5.25 ± 0.30^{b}	4.65 ± 0.60^{ab}	3.19 ± 0.40^{a}
Delamination (%)	32.43 ± 5.02^{b}	22.60 ± 0.61^{a}	16.00 ± 3.22^{a}	14.96 ± 3.72^{a}

Table 2. Bending properties of three-layer plybamboo board by steam-treatment duration. Mean ± SD (n = 3 independent panels). Different lowercase letters within a row denote significant differences (Tukey's HSD test, $p < 0.05$), with letters ascending with the group mean; n.s. = not significant. As-measured values in kg cm^{-2} are given in parentheses.

Property	Control (0 min)	30 min	45 min	60 min
$MOE_{\parallel}$ grain (GPa)	2.03 ± 0.17^{a}	3.69 ± 0.59^{b}	2.66 ± 0.49^{ab}	2.15 ± 0.12^{a}
(kg cm^{-2})	(20697)	(37650)	(27150)	(21900)
$MOE_{\perp}$ grain (GPa)	0.63 ± 0.02	0.68 ± 0.07	0.59 ± 0.09	0.60 ± 0.11 (n.s.)
(kg cm^{-2})	(6438)	(6974)	(5976)	(6069)
$MOR_{\parallel}$ grain (MPa)	27.7 ± 2.2^{a}	43.1 ± 5.9^{b}	28.2 ± 4.1^{a}	26.4 ± 1.8^{a}
(kg cm^{-2})	(282)	(439)	(288)	(269)
$MOR_{\perp}$ grain (MPa)	15.8 ± 2.3	17.0 ± 2.1	15.4 ± 0.5	15.1 ± 2.5 (n.s.)
(kg cm^{-2})	(161)	(173)	(157)	(154)
Specific $MOE_{\parallel}$ (GPa / (g cm^{-3}))	3.83 ± 0.32^{a}	6.27 ± 1.13^{b}	4.58 ± 0.75^{ab}	4.77 ± 0.26^{ab}
Specific $MOR_{\parallel}$ (MPa / (g cm^{-3}))	52.3 ± 5.8^{ab}	73.2 ± 12.2^{b}	48.9 ± 8.5^{a}	58.6 ± 4.2^{ab}
Anisotropy $MOE_{\parallel}/MOE_{\perp}$ (–)	3.22 ± 0.34	5.40 ± 0.77	4.66 ± 1.41	3.66 ± 0.45 (n.s.)

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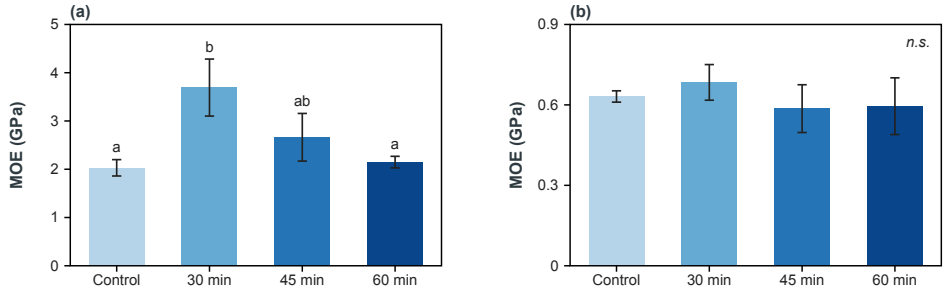


Figure 3. Modulus of elasticity (MOE) of plybamboo board (a) parallel and (b) perpendicular to the grain as affected by steam-treatment duration. Bars are mean ± SD (n = 3 independent panels); different letters denote significant differences (Tukey's HSD test, $p < 0.05$); n.s. = not significant.

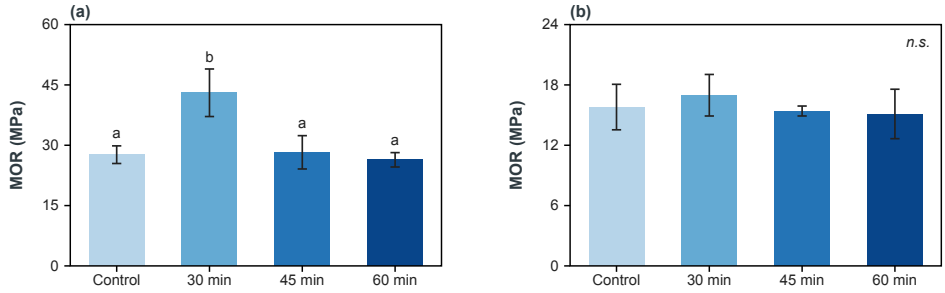


Figure 4. Modulus of rupture (MOR) of plybamboo board (a) parallel and (b) perpendicular to the grain as affected by steam-treatment duration. Bars are mean ± SD (n = 3 independent panels); different letters denote significant differences (Tukey's HSD test, $p < 0.05$); n.s. = not significant.

group. The 30 min peak parallels the density trend, suggesting a strong density contribution to stiffness in this direction [31,32]. Perpendicular-grain MOE, by contrast, showed no significant treatment effect ($F(3, 8) = 0.99$, $p = 0.446$): steam modification acts on the face-grain (load-aligned) direction and leaves the cross-ply direction essentially unchanged. No treatment, in either direction, reached the SNI 01-5008.7-1999 requirement for 15-mm structural plywood (>4.90 GPa (50 000 kg cm^{-2}) parallel; >3.92 GPa (40 000 kg cm^{-2}) perpendicular).

The rise-and-fall time course matches the chemistry of saturated-steam modification observed at higher severities, where the same window is compressed: in moso bamboo, flexural strength and modulus increase over roughly the first 20 min of exposure and decline thereafter as hemicellulose is progressively removed [17], and over-treatment reduces MOR by 47% and MOE by 20% relative to untreated controls [16]. The 30 min optimum found here at the milder severity of 126 °C sits where the bonding gain from extractive degradation still outweighs the matrix loss from hemicellulose hydrolysis; by 60 min the balance has inverted.

3.2.2 Modulus of Rupture

Parallel-grain MOR followed the same pattern ($F(3, 8) = 12.3$, $p = 0.002$, $\eta^2 = 0.82$), rising from 27.7 MPa in the control to 43.1 MPa at 30 min (a 56% gain), then returning to control-level values at 45 and 60 min; only the 30 min treatment differed significantly from the others. Perpendicular-grain MOR was not significantly affected ($F(3, 8) = 0.51$, $p = 0.685$). In the parallel direction every treatment, including the control, exceeded the SNI 01-5008.7-1999 requirement of >19.6 MPa (200 kg cm^{-2}), whereas the perpendicular-grain values fell short of the corresponding threshold.

3.3 Densification or Substrate Improvement?

Because the 30 min treatment produced both the stiffest and the densest boards, the mechanical gain could in principle be a by-product of densification alone. Two observations from the same data set show that it is not. First, the specific bending properties — each panel's MOE∥ and MOR∥ divided by its own density — remain significantly affected by treatment (specific MOE: $F(3, 8) = 6.22$, $p = 0.017$, $\eta^2 = 0.70$; specific MOR: $F(3, 8) = 5.13$, $p = 0.029$; Table 2). Specific MOE rises from 3.83 GPa per g cm^{-3} in the control to 6.27 GPa per g cm^{-3} at 30 min — a 64% gain that survives density normalisation — before falling back to intermediate values at longer durations. Second, regressing the twelve panels' bending properties on their densities (Fig. 5) shows that density explains only 40% of the variance in MOE∥ ($R^2 = 0.40$, $p = 0.027$) and none of the variance in MOR∥ statistically ($R^2 = 0.22$, $p = 0.126$); at comparable densities of 0.55–0.62 g cm^{-3} , the 30 min panels lie clearly above the control and 45 min panels. These observations are consistent with an improvement in the slat–bond-line system beyond the contribution of bulk density alone. Improved wetting and resin–substrate contact are possible explanations, but were not directly measured and cannot be established from density normalisation or pooled regression. The stiffness anisotropy ratio MOE∥ /MOE⊥ rose from 3.2 in the control to 5.4 at 30 min but the effect did not reach significance ($F(3, 8) = 4.01$, $p = 0.052$), consistent with the treatment acting on the load-aligned face layers while leaving the cross-ply direction unchanged.

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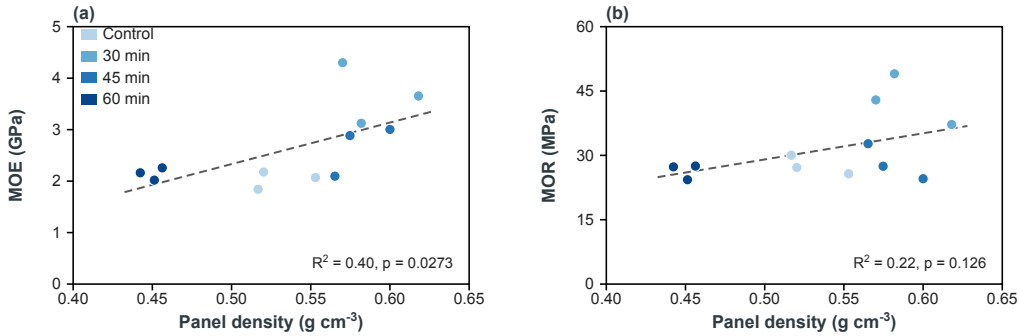


Figure 5. (a) Parallel-grain MOE and (b) parallel-grain MOR of the twelve individual panels against their densities, pooled across treatments. Dashed lines are ordinary-least-squares fits; R^2 and p are given in each panel.

Table 3. Comparison of the present plybamboo boards with related bamboo-oriented strand boards and the selected structural-plywood benchmark. BOSB ranges span untreated to steam-treated panels; source values in kg cm^{-2} were converted to SI. The plywood thresholds are comparative reference values and do not certify bamboo-product compliance.

Panel	Binder / press	ρ (g cm^{-3})	$MOE_{\parallel}$ (GPa)	$MOR_{\parallel}$ (MPa)	TS (%)
PBB betung, 30 min (this study)	PVAc / cold	0.59	3.69	43.1	5.3
PBB betung, 60 min (this study)	PVAc / cold	0.45	2.15	26.4	3.2
BOSB betung [22]	PF / hot	0.71–0.72	8.0–11.3	51–75	5.9–7.5
BOSB andong [22]	PF / hot	0.70–0.73	6.9–9.9	39–68	8.8–9.8
SNI 01-5008.7-1999 (15 mm) [30]	—	—	>4.90	>19.6	—

3.4 Synthesis: What Limits Sustainable Plybamboo

Two messages emerge. First, if the design priority is stiffness and bending strength, a short 30 min steam treatment is optimal: it alone maximises parallel-grain MOE and MOR and yields the highest density, while 45 and 60 min trade mechanical performance for further gains in water resistance. Second, if the priority is dimensional stability and bond durability — the properties that matter most for interior and humid-service panels — WA, TS, and delamination all continue to improve to 60 min, so a longer treatment is preferable. The "best" duration is therefore application-dependent rather than universal. Table 3 places the boards in the context of related bamboo panels and the structural-plywood threshold. Strand boards made from the same species with the same steaming protocol, but hot-pressed with phenol formaldehyde to densities near 0.7 g cm^{-3} , reach parallel-grain moduli of 8–11 GPa [22]; the gap between those boards and the present ones tracks the binder, the pressing route, and the achieved density, not the substrate treatment, which is shared. The same reading holds across the wider panel literature: bamboo scrimber reaches timber-competitive properties through far higher densification [12], while strand boards from mixed and underutilised wood furnish [33,34] and bamboo–wood hybrid panels [35] occupy the same density-governed property landscape. Against green chemical routes the comparison favours steaming: citric-acid–boron esterification of *D. asper* lowers water absorption by 26% and thickness swelling by 43% at the cost of a ∼30% loss in tensile strength [36], whereas water-only steaming here achieved a comparable WA reduction (29%) and a larger TS reduction (65%), with a strength gain at the 30 min optimum. Two performance limitations persisted across the durations tested: bending properties below the selected plywood benchmarks and residual delamination. Stiffness (MOE in both directions, and perpendicular-grain MOR) never reached the SNI 01-5008.7-1999 thresholds. The specific-property analysis sharpens what closing this gap requires: taking the best (30 min) substrate at its specific stiffness of 6.27 GPa per g cm^{-3} , a panel at the 0.7 g cm^{-3} target density would, to first order, reach only about 4.4 GPa — still some 10% below the 4.90 GPa threshold. Densification to the target density is therefore necessary but not quite sufficient; it must be combined with a higher compression ratio during pressing, which raises stiffness beyond the proportional effect through surface densification [25,31,37,38], or with a revised lay-up that thickens the load-aligned face layers. Residual delamination warrants evaluation of both adhesive formulation and application, including spread rate and single versus double spreading, alongside more moisture-durable adhesive options [14,23,39,40]. The present design does not distinguish adhesive chemistry from incomplete adhesive transfer or coverage. Densification and bond-line design are therefore priorities for further study, while the unverified delamination cycle count limits durability comparisons.

These boards, as made, are best positioned not as structural plywood substitutes but as sustainable non-structural panels — interior partitions, furniture cores, cabinetry, and cladding for humid tropical service — where their large gains in dimensional stability, formaldehyde-free bonding, and rapidly renewable feedstock are decisive advantages and where the structural MOE threshold is not the binding requirement.

3.5 Limitations

Several limitations bound these conclusions. First, each treatment was represented by three panels (n = 3); although every ANOVA assumption test was satisfied and the main effects are large (η^2 = 0.70–0.96), small samples limit the power of post-hoc separations, and the marginal anisotropy effect (p = 0.052) in particular warrants re-testing at larger n. Second, a single steam severity (126 °C, 0.14 MPa) was studied, so the

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duration optimum reported here cannot be extrapolated to other temperatures, where the treatment window is known to shift [16,17]. Third, the chemical interpretation rests on compositional changes reported for the same species and protocol in the literature [14,17] rather than on measurements of these particular slats. Fourth, the delamination values are a relative index from a soak–dry cycle adapted from JAS 234 [29] rather than a standardised bond-quality metric, and the specific properties pair bending and density specimens cut from the same panel, which assumes within-panel homogeneity. In addition, uniform wetting under single spreading was not directly verified. Relative humidity was neither controlled nor numerically documented during conditioning and testing, so the moisture content represents the ambient laboratory state and should not be interpreted as an equilibrium value at a specified RH. The delamination cycle count could not be recovered from the available documentation; this prevents exact reproduction of that exposure and restricts interpretation of the delamination results. Finally, plywood thresholds were used only as comparative benchmarks and do not constitute certification of this bamboo product.

4. CONCLUSIONS

Steaming betung slats at 126 °C significantly altered the physical and mechanical properties of three-layer, PVAc-bonded plybamboo board, with duration setting both the direction and the magnitude of the changes. A short 30 min treatment produced the best mechanical profile, maximising parallel-grain MOE (+82%) and MOR (+56%) and giving the highest density, while perpendicular-grain bending was statistically unchanged. This gain survives density normalisation — specific parallel-grain MOE rose 64%, and density explains only 40% of the cross-panel variance in MOE — supporting an improvement beyond bulk densification, although the proposed wetting mechanism remains unverified. Extending treatment to 45 or 60 min continued to improve dimensional stability — thickness swelling and delamination fell by up to 65% and 54% — but progressively lowered density and strength, consistent with hemicellulose depolymerisation outweighing extractive-driven bonding gains at longer exposure. The measured moisture contents were below the SNI 8032:2014 reference limit and parallel-grain bending strengths exceeded the SNI 01-5008.7-1999 reference value, but none reached the 0.7 g cm^{-3} target density, and MOE in both directions and perpendicular-grain MOR fell short of the structural thresholds. Within this green, water-only process the residual gaps call for different, non-thermal fixes: for stiffness, densification to the target density is necessary but not sufficient — a first-order extrapolation of the best substrate reaches about 4.4 GPa, still below the 4.90 GPa threshold — so a higher compression ratio or a face-weighted lay-up is required, whereas residual delamination calls for evaluation of adhesive durability and application uniformity. A 30 min steam treatment is the recommended pretreatment where strength governs, and a longer treatment where dimensional stability governs; in both cases the product is best deployed as a sustainable, non-structural bamboo panel. These comparisons do not establish structural certification. The undocumented RH and unverified soak–dry cycle count restrict moisture-related and durability interpretation. Future work should quantify density–adhesive combinations under controlled conditioning and a fully documented delamination protocol.

AUTHOR CONTRIBUTIONS

Sena Maulana: Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **Muhammad Saeful Fadlan:** Investigation, Formal analysis, Writing – original draft. **Muhammad Iqbal Maulana:** Methodology, Investigation, Writing – review & editing. **Sarah Augustina:** Formal analysis, Data curation, Writing – review & editing. **Byantara Darsan Purusatama:** Methodology, Validation, Writing – review & editing. **Muhammad Aizat Abd Ghani:** Validation, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

USE OF AI-ASSISTED TECHNOLOGIES

Generative-AI tools were used during the preparation of this manuscript for language editing and to assist in writing the data-analysis and figure-generation scripts. All experimental data are the authors' own, all reported statistics were computed from those data, and every AI-assisted output was reviewed and verified by the authors. The authors take full responsibility for the content of this manuscript.

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