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ENHANCING THE PHYSICO-MECHANICAL PROPERTIES OF PHILIPPINE BAMBOOS THROUGH SPENT COOKING OIL HEAT TREATMENT

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Thermal modification (TM) through spent cooking oil heat treatment (SCOHT) was applied to giant bamboo (*Dendrocalamus asper* (Schult.) Backer) and kauayan-tinik (*Bambusa spinosa* Roxb.) to evaluate their physico-mechanical properties. Bamboo samples underwent SCOHT at 175°C and 200°C for 30 min and 60 min using a fabricated laboratory boiling vat. SCOHT significantly reduced moisture content (MC) from 11.10% (control) to 3.97% (200°C-30 min), and relative density (RD) from 0.70 (control) to 0.58 (200°C-60 min). Thickness swelling (TS) and water absorption (WA) were reduced by up to 79% and 69%, respectively. Water contact angle (CA) increased from 62.88° (control) to 81.75° (200°C-60 min), indicating enhanced hydrophobicity. Meanwhile, the mechanical properties, particularly the modulus of rupture (MOR) and modulus of elasticity (MOE), were not significantly affected. *B. spinosa* exhibited higher values than *D. asper* in terms *of* RD (0.66 vs. 0.59), MOR (147.31 MPa vs. 122.43 MPa), and MOE (16.28 GPa vs. 12.00 GPa), but lower TS (1.82% vs. 2.45%) and WA (13.30% vs. 17.00%). These findings suggest that SCOHT enhances the bamboos' dimensional stability and water resistance without compromising their bending properties. The increased hydrophobicity poses considerations in bamboo composite production, particularly on surface energy activation and adhesive selection.

Keywords: Thermal modification, wettability, dimensional stability, hydrophobicity, contact angle, bamboo composites, flexural strength

INTRODUCTION

Bamboo is deeply integrated into the cultural and socio-economic fabric of the Philippines, serving as one of the fundamental materials for light to medium construction, handicrafts and furniture, and other advanced applications such as biofuel production, pollutant adsorption, and energy storage (Richard et al. 2017, Salzer et al. 2017, 2018, Bondad et al. 2023, Lou et al. 2023). At present, the urgent need to tap bamboo resources in the country as an alternative to woody materials arises from an inadequate supply of timber due to persistent demand for wood-based commodities, while depletion of conventional forest resources continues to rampant deforestation (Del Castillo 2021, Gabriel 2023). Rapid growth rate, high strength-to-weight-ratio, and natural aesthetic appeal have rendered bamboo as a promising, versatile, and sustainable alternative to wood (Kaur et al. 2019, Lou et al. 2023).

Among the bamboo products mainstreamed in the Philippines, engineered bamboo or e-bamboo stands out for its potential to replace traditional wood in various applications. Generally, e-bamboo is a reconstituted composite material made by breaking down the entire bamboo culm into smaller pieces and bonding these together into a composite panel or dimensioned lumber with adhesives typically used in the wood industry (Liu et al. 2015). The country has recognized the export potential of this product amid growing global demand (Gil 2024). In response, the Board of Investments, the Philippine Bamboo Industry Development Council (PBDIC), and the Department of Trade and Industry (DTI) have included the strengthening of the local e-bamboo industry in the PBDIC Roadmap's short-, medium- and long-term goals (DTI 2023).

Despite its inherent physico-mechanical advantages, bamboo as a raw material still has limitations. Like other lignocellulosic materials, its hygroscopicity leads to cyclic moisture absorption and desorption to achieve equilibrium with the prevailing environmental moisture conditions (Anokye et al. 2016, Yuan et al. 2021, Mou et al. 2022) resulting in warping, cracking, and loss of structural integrity over time. Moreover, it is also susceptible to biological degradation by insects and fungi, which can compromise its durability (Kaur et al. 2019, Jimenez & Rizare 2024). To address these inadequacies, thermal modification (TM) offers a non-chemical approach to enhance bamboo's properties, with studies demonstrating its effect on its material properties (Sulaiman et al. 2006, Bremer et al. 2013, Li et al. 2015, Bui et al. 2017, Lee et al. 2018, Tang et al. 2019a, 2019b, Lou et al. 2020, Wang et al. 2020a, 2020b, Hao et al. 2021, Piao et al. 2022). This method is well-established in some European countries (Sandberg & Kutnar 2015), but still in the early stages in the Philippines, with limited research and development conducted (Manalo & Acda 2009, Jimenez et al. 2011, 2021, Marasigan et al. 2020, Ramos et al. 2022, Quintos et al. 2023, Jimenez & Ramos 2024). Among the established TM techniques, oil as a treatment medium is notable for its dual function: acts as a heat transfer medium and as a modifier that enhances the bamboo surface's hydrophobicity (Jimenez & Ramos 2025, Li et al. 2015, Tang et al. 2019b).

This present study investigated the impact of spent cooking oil heat treatment (SCOHT) on giant bamboo (*Dendrocalamus asper* (Schult.) Backer) and kauayan-tinik (*Bambusa spinosa* Roxb.), two of the country's commercially important bamboo species (Razal et al. 2012). It evaluated the effects of SCOHT on dimensional stability, wettability, and mechanical strength (relative density and static bending) to determine its potential as a viable TM method of enhancing bamboo's performance for structural and non-structural applications. Also, examining the wettability will enhance further understanding of solvent interactions with TM bamboo, supporting advances in bamboo-based composites and e-bamboo production in the country.

MATERIALS AND METHODS

Bamboo Collection

Three-year-old *D. asper* and *B. spinosa* culms were obtained from Carolina Bamboo Garden in Antipolo, Rizal Province, Philippines and transported to the Department of Science and Technology - Forest Products Research and Development Institute (DOST-FPRDI) for further processing. Five poles (bottom portion) free from visible defects were selected for each species based on the straightness of internodes with a minimum length of 40 cm. The eighth internode from the base of each pole was extracted using a bamboo pole cutter. These internodes were then split longitudinally into smaller sections using a bamboo splitter, resulting in 30 splits for each bamboo species. The splits were dried at 70°C for 48 h to achieve an average moisture content (MC) of 11%. Five representative splits from each internode were randomly assigned into five treatment classes (Table 1). The initial weight of the splits under the treatment group A was measured after drying.

Spent Cooking Oil Acquisition

This study's selection of spent cooking oil was driven by sustainable practices to divert waste and utilize this readily available input for thermal treatment. Moreover, it offered a more cost-effective alternative compared with unused commercial oils. Spent cooking oil was obtained from Sardido Industries, Inc., a Department of Environment and Natural Resources-accredited hauler and treater of used oils in Tanza, Cavite Province, Philippines. According to the supplier, the used cooking oil was sourced from resorts and hotels in San Juan, Batangas Province, Philippines, excluding major fast-food chains. The oil underwent gravitational filtration to allow separation of oil and water through settling, achieving an estimated 95% water removal. Prior to SCOHT, the oil had an initial average temperature, pH, and viscosity of 27°C, 6.37, and 110 cP, respectively.

Table 1 Treatment classes for SCOHT

	Treatment Groups	SCOHT Temperature (°C)	SCOHT Duration (min)
D. asper	Control	-	-
	A	175	30
	B	175	60
	C	200	30
	D	200	60
B. spinosa	Control	-	-
	A	175	30
	B	175	60
	C	200	30
	D	200	60

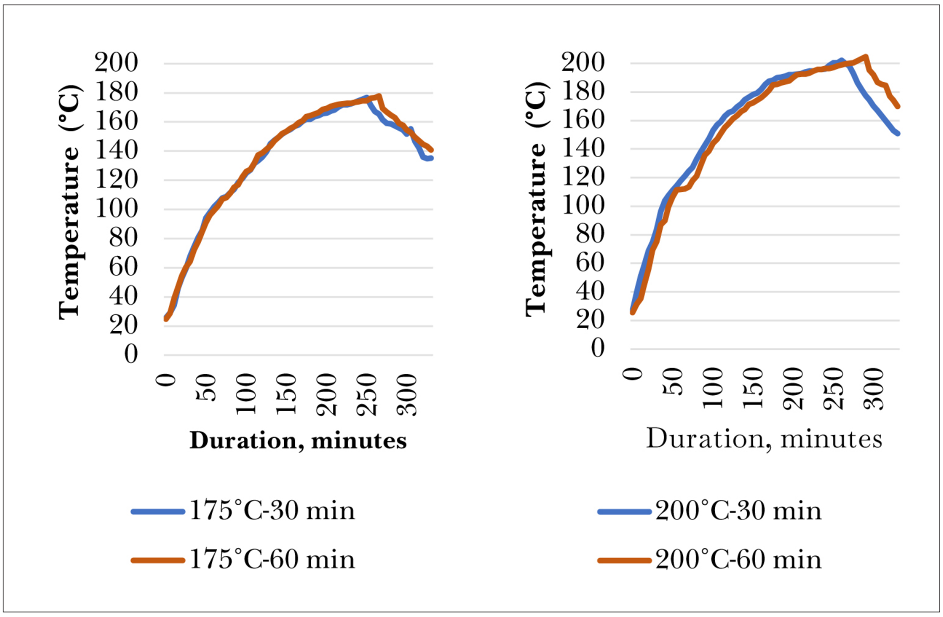

Figure 1 Temperature increases of the laboratory hot plate during SCOHT for target exposures of 175°C (left) and 200°C (right)

Thermal Modification

SCOHT was performed at DOST-FPRDI. Before the treatments, the initial weight of each bamboo split was measured. A fabricated stainless-steel boiling vat equipped with a 5000-W laboratory hot plate connected to a digital temperature controller was filled with spent cooking oil. Bamboo splits were placed in the vat and metal weights were attached to the submersible loading frames to ensure the splits' complete submersion throughout the process. The spent cooking oil was heated to the target temperatures (±5°C) based on the requirements in Table 1, and its surface temperature continuously monitored throughout the treatment duration using an infrared thermometer (Fluke 62 MAX). Treatment duration started once the oil reached the target temperatures, which were achieved after an average of 215 min (175°C) and 230 min (200°C) (Figure 1). Once the target exposure duration was reached, the hot plate was switched off and the temperature allowed to gradually decrease to cool it down.

Following the treatment, the samples were removed from the oil and conditioned for one week at controlled room temperature (25°C) and relative humidity (65%). Residual oil on the surface of the splits was carefully removed after the conditioning period. The splits were then trimmed further of their inner (pith) and outer (skin) surfaces to produce slats.

Moisture Content and Relative Density

Moisture content (MC) was determined following ASTM D143-22 (ASTM 2023) procedure with some modifications on the sample size. Small samples (25 mm × actual thickness × 25 mm) cut from the flexural test specimens were weighed initially. These were then oven-dried at 103°C until a constant weight was achieved (at least 24 h). The MC was calculated as a percentage based on the change in weight over the oven-dry weight.

Relative density (RD) followed ASTM D2395-17 (ASTM 2017), with modifications in sample size. Via water immersion test, a setup using a balance, distilled water-filled beaker, and metal rod was used. The balance was initially tared with the beaker containing water. Each sample was then attached to the rod and carefully submerged in the water. The weight reading on the balance at this point represented the volume of water displaced by the sample, which was equivalent to the sample's volume. The samples were oven-dried at the same temperature (103°C) until a constant weight was achieved. RD was calculated as the ratio of each sample's oven-dry weight to its volume.

Thickness Swelling and Water Absorption

Five replicates from the slats of each treatment class were cut into uniform dimension of 25 mm (width) × actual thickness × 38 mm (length). The initial weight of each sample was recorded using a digital balance (precision of 0.0001 g), and its initial thickness measured using a digital calliper.

Samples from each treatment class were immersed in distilled water at room temperature (19°C). Weights were added to the setup to ensure all samples were fully submerged throughout the soaking periods. The weight and thickness of each sample were recorded after 24 h of soaking. Thickness swelling (TS) and water absorption (WA) percentage values were computed using Equations 1 and 2, respectively.

$$\text{WA}\ (\%) = \frac{w_g - w_i}{w_i} \times 100 \qquad (1)$$

where w_g is the weight of the sample after soaking, and w_i is the weight of the sample before soaking.

$$\text{TS}\ (\%) = \frac{t_g - t_i}{t_i} \times 100 \qquad (2)$$

where t_g is the thickness of the sample after soaking and t_i is the thickness of the sample before soaking.

Wettability

The bamboo samples' wettability was evaluated using the sessile drop method with distilled water as the test solvent. This method quantitatively measured the water droplet's contact angle on the surfaces of untreated and SCOHT bamboo. A micropipette was used to deposit 5 μL droplets of distilled water on the surface of three randomly selected splits per treatment class. The droplet was dispensed at designated locations (left, middle, and right) on both the inner and outer surfaces of the bamboo splits. A digital camera positioned approximately 25 cm from the edge of the bamboo specimen captured images of the droplets after a settling time of two seconds. The captured drop images were processed using ImageJ's (version 1.52a) LB-ADSA (Low Bond Axisymmetric Drops Shape Analyzer) to determine the contact angle.

Static Bending

Static bending test was performed following ASTM D143-22 (ASTM 2023) with some modifications on the testing sample dimensions. Five replicates from each treatment class were cut into uniform dimensions of 25 mm (width) × actual thickness × 304 mm (length). The exact initial dimensions of each sample were recorded before testing. Flexural properties (MOR and MOE) were evaluated using a three-point bending test on a Universal Testing Machine (UTM). The test was conducted at a constant crosshead speed of 5 mm/min. During the test, the bamboo sample's cutin surface (convex side) was oriented on the compression side of the bending setup.

Data Analysis

Two-factor factorial in CRD was used for most of the analyses (MC, RD, TS, WA, MOR, and MOE). The design considered two factors: bamboo species (*D. asper* and *B. spinosa*) and temperature-duration (°C-min) combinations (control, 175-30, 175-60, 200-30, 200-60). Meanwhile, the three-factor factorial in CRD was used for the wettability test, which added the bamboo's surface (skin and pith) as the third factor. Using RStudio, ANOVA was employed for each parameter to assess the statistical significance of the main effects and their interaction. Meanwhile, Tukey's Honest Significance Difference (HSD) test was applied for pairwise comparison among the means of significant factors or interactions identified in the ANOVA.

RESULTS AND DISCUSSION

Moisture Content

The ANOVA (Table 2) revealed that SCOHT significantly reduced the MC of both bamboo species. However, there were no significant differences between species and interactions of the factors (treatment class x species).

The MC of the treated groups ranged from 3.97% (200-30) to 4.29% (175-30), which was lower by 61%–64% than the control's 11.10% MC (Figure 2). While the MCs of the oil-treated groups did not significantly differ, their MCs relative to the control indicates that SCOHT effectively removed the moisture from the bamboo. Moreover, the lack of significant difference between treatment durations and temperature levels suggests that moderate heat

Table 2 ANOVA on MC and RD of oil-heat treated *D. asper* and *B. spinosa*

Sources of Variation	Degrees of Freedom	MC (%)		RD	
		F-value	*p*-value	F-value	*p*-value
Species (S)	1	0.089	0.767^{ns}	20.489	<0.001**
Treatment (T)	4	117.946	<0.001**	8.075	<0.001**
S x T	4	0.060	0.993^{ns}	0.402	0.806^{ns}

**statistically significant at the 1% level
ns - not statistically significant

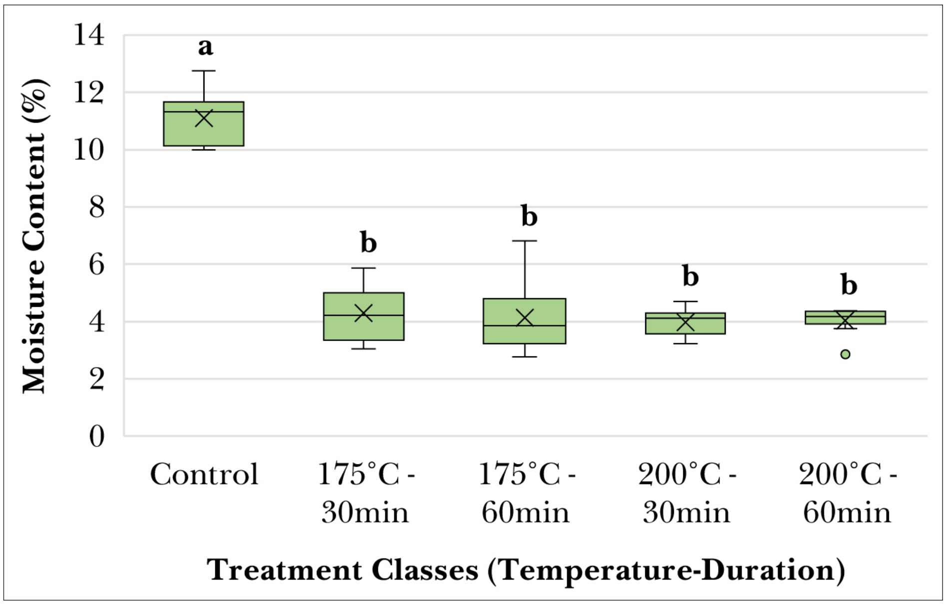

Figure 2 Box and whiskers plot of the MC across different treatment classes of SCOHT. Letters indicate Tukey's HSD grouping; treatment classes with the same letter are not significantly different at the 1% level

Table 3 Mean physico-mechanical properties of oil-treated *D. asper* and *B. spinosa* with species as source of variation

Source of Variation	Physical				Mechanical	
	MC (%)	RD	TS (%)	WA (%)	MOR (MPa)	MOE (GPa)
D. asper	5.47[a] *(0.58)*	0.58[a] *(0.01)*	2.45[a] *(0.40)*	17.00[a] *(1.44)*	122.43[a] *(7.01)*	12.00[a] *(0.51)*
B. spinosa	5.54[a] *(0.61)*	0.66[b] *(0.02)*	1.82[a] *(0.38)*	13.30[b] *(1.43)*	147.31[b] *(9.03)*	16.28[b] *(0.51)*

Values in parentheses are standard errors of the mean. Means denoted by the same letter(s) are not significantly different according to Tukey's HSD post hoc test

treatment was sufficient to reduce moisture substantially.

This behaviour has also been observed in TM studies on other types of oil as treatment media such as tung oil (Tang et al. 2019b), sunflower oil (Bui et al. 2017), and methyl silicone oil (Yuan et al. 2020, Hao et al. 2021). This is attributed to the heating process which drives out moisture through evaporation and causes internal stress, leading to deformation of the parenchyma pits and weakening of the dense structure of parenchyma cell walls (Hao et al. 2021, Jimenez & Ramos 2024).

Relative Density

ANOVA revealed the significant effects of both bamboo species and SCOHT on the samples' RD, while the interaction of these factors was not statistically significant (Table 2). *B. spinosa* was observed to be denser than *D. asper* by 12% (Table 3). This significant difference can be attributed to variations in cellular structure and fibre composition of the bamboo species (Liese & Tang 2015, Siam et al. 2019).

SCOHT generally reduced RD, which was consistent across both species (Figure 3). While no significant difference in the recorded RDs was observed between the heat treatment durations, Tukey's HSD analysis revealed three distinct groups in the temperature level exposures: the control group with the highest RD, and the 175°C and 200°C groups with reduced RDs of 10% and 17%, respectively.

Despite a general decline in RDs in other studies at intensified temperature levels (Yang et al. 2016, Tang et al. 2019a, Jimenez & Ramos 2024), the RD drop observed in this study was comparatively higher. For example, Tang et al. (2019a) recorded only 2% and 6% decrease at 180°C and 200°C, respectively, compared to the control in their TM of moso bamboo (*Phyllostachy edulis*) for 3 h using tung oil. The differing results can be explained by the potential limitation in this study wherein the Fluke infrared thermometer used to monitor the oil bath temperature can measure surface temperatures. In this case, the bamboo samples within the oil bath might have experienced higher internal temperatures. Employing probes to monitor the internal temperature of bamboo samples during the oil heat treatment process may be beneficial to future studies.

The general decline in the RD of oil-heat treated bamboo is attributed to the changes in its structure and chemical composition caused by TM. Studies have shown that exposure to elevated temperatures (180°C to 240°C) leads to the degradation of hemicellulose and the amorphous regions of cellulose, with significant mass loss ranging from 11% to 18%, depending on the treatment conditions (Hao et al. 2021, Zhang et al. 2024). The reduction in cellulose content is primarily due to the volatilization of degradation products, while the significant decrease in hemicellulose is attributed to its poor thermal stability and susceptibility to hydrolysis (Hao et al. 2021). As major components of bamboo's cell wall, their degradation leads to a decrease in RD due to mass loss and weakened structural integrity (Nguyen et al. 2012, Liese & Tang 2015, Yang et al. 2016, Zakikhani et al. 2016, Yuan et al. 2022).

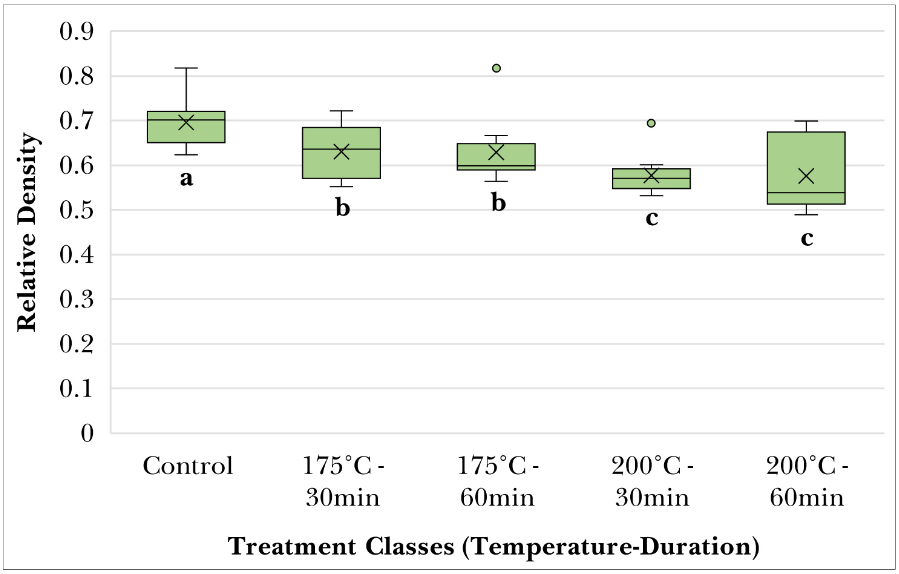

Figure 3 Box and whiskers plot of the RD across different treatment classes of SCOHT. Letters indicate Tukey's HSD grouping; treatment classes with the same letter are not significantly different at the 1% level

Table 4 ANOVA on thickness swelling (TS) and water absorption (WA) of oil-heat treated *D. asper* and *B. spinosa*

Sources of Variation	Degrees of Freedom	TS (%)		WA (%)	
		F-value	*p*-value	F-value	*p*-value
Species (S)	1	2.792	0.103^{ns}	9.961	0.003**
Treatment (T)	4	15.137	<0.001**	25.263	<0.001**
S x T	4	0.061	0.993^{ns}	0.811	0.525^{ns}

**statistically significant at the 1% level
ns - not statistically significant

Moreover, the thermal breakdown of hemicellulose produces acidic compounds that may further hydrolyse cell wall components, potentially reducing the bamboo's mechanical strength, as shown by the RD reduction (Zhang et al. 2024). And, while compaction of cell wall occurs which favours dimensional stability, the overall reduction in mass leads to a net decrease in RD (Zhang et al. 2024). With further significant reduction of RD at heightened temperature exposure, a moderate heat treatment is sufficient to induce minimal change in RD.

Thickness Swelling and Water Absorption

Bamboos' dimensional stability, as reflected in thickness swelling (TS) and water absorption (WA), was significantly affected by SCOHT based on the ANOVA results (Table 4). Compared to the control, the treated samples' TS and WA were reduced by 65%-79% and 30%-69%, respectively (Figure. 4). Tukey's post hoc test revealed a dose-dependent effect of SCOHT on WA wherein higher temperature resulted in a more significant reduction than a lower temperature exposure. Neither parameter was significantly affected by the treatment's duration of exposure.

The substantial reduction in TS and WA values observed in all heat-treated groups indicates the effectiveness of SCOHT in improving bamboo's dimensional stability. The inherent non-polarity of the oil used as the treatment medium significantly enhances the bamboo's hydrophobicity (Silverstein 1998). The treatment partially modifies the surface

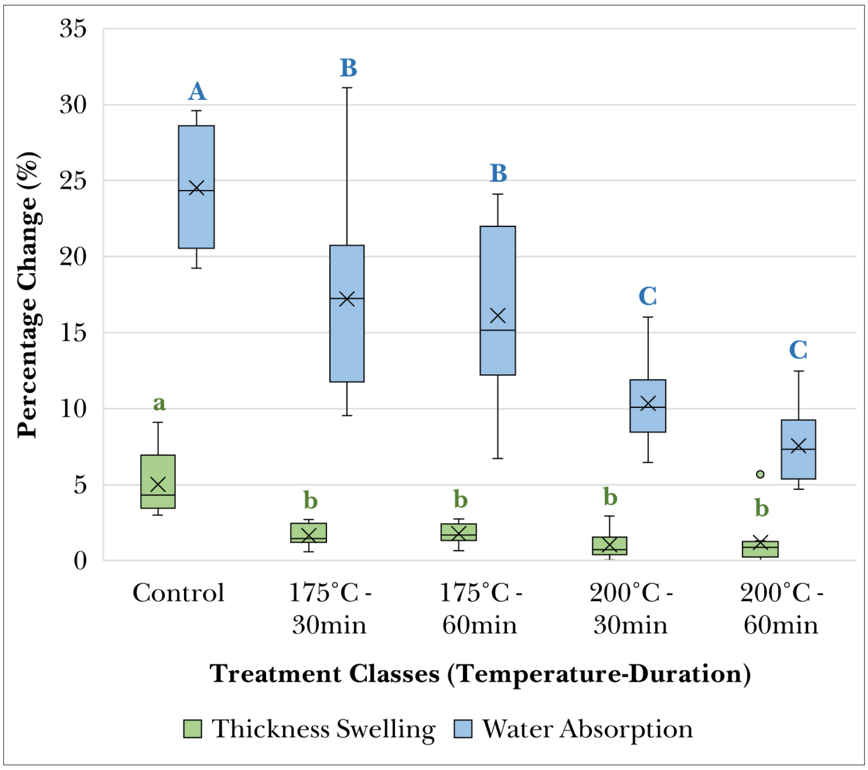

Figure 4 Box and whiskers plot of the TS and WA across different treatment classes of SCOHT. For each parameter, letters indicate Tukey's HSD grouping, and treatment classes with the same letter are not significantly different at the 1% level

chemistry of the bamboo, making it more hydrophobic, which hinders water absorption and minimizes swelling.

These improvements can also be accounted for by the decomposition of hydrophilic hemicellulose caused by treatment exposure, which is known for its low thermal stability under high temperatures (Farhat et al. 2017, Xiao et al. 2022). Anatomically, the bamboo's cell walls consist of several pits and act as connections between adjacent tissues. After oil-heat treatment, the cell walls, cell lumens, and intercellular spaces are coated with an oily film, while the pits are obstructed with oil which restricts the water transport pathways (Hao et al. 2021, Tang et al. 2022). Meanwhile, oil can be present in the parenchyma cell lumen and along the vessel pathways following oil-heat treatment, demonstrating the penetration of oil into the bamboo structure (Hao et al. 2021). These structural modifications impart hydrophobic and dimensionally stable properties to SCOHT bamboo.

The observed reduction in TS and WA after SCOHT indicates enhanced resistance of bamboo to moisture-related issues, thereby minimizing shrinking and swelling caused by moisture fluctuations in the environment. This in turn improves the durability and workability of bamboo products, and resistance to biological degradation caused by insects and fungi which thrive in moist environments.

Wettability

Wettability, an indication of a material's surface interaction with a liquid, was evaluated via the sessile drop method by measuring the contact angle of water on the bamboo's surfaces. ANOVA revealed statistical significance in the wettability for factors including species, SCOHT, and the interaction between these two factors (Table 5). Interestingly, the study was not able to capture any significant difference in wettability on the bamboo's surface.

B. spinosa exhibited a naturally more hydrophobic surface than *D. asper*, with a measured average contact angle that was 9% higher (Table 6). Meanwhile, the average contact angle of water on oil-heat treated bamboo was significantly higher than in the control, with a 9%–30% observed increase. Though Tukey's

Table 5 ANOVA on the wettability of oil-heat treated *D. asper* and *B. spinosa*

Sources of Variation	Degrees of Freedom	Wettability (°)	
		F-value	*p*-value
Species (Sp)	1	39.961	<0.001**
Treatment (T)	4	38.674	<0.001**
Surface (S)	1	0.168	0.683[ns]
Sp x T	4	3.306	0.0147*
Sp x S	1	2.912	0.092[ns]
T x S	4	0.653	0.626[ns]
Sp x T x S	4	0.427	0.789[ns]

** statistically significant at the 1% level
*statistically significant at the 5% level
ns - not statistically significant

Table 6 Mean contact angle of oil-heat treated *D. asper* and *B. spinosa* with species, treatment classes and species-treatment class interaction as sources of variation

Sources of Variation	Contact Angle (°)
Species	
D. asper	69.01[a]
B. spinosa	75.83[b]
Treatment Classes	
Control	62.88[a]
175-30	68.48[b]
175-60	71.10[b]
200-30	77.86[c]
200-60	81.75[c]
Species x Treatment Class	
D. asper x Control	59.49[a]
D. asper x 175-30	62.87[a]
D. asper x 175-60	65.57[a]
D. asper x 200-30	76.06[bc]
D. asper x 200-60	81.05[bc]
B. spinosa x Control	66.27[a]
B. spinosa x 175-30	74.08[b]
B. spinosa x 175-60	76.64[bc]
B. spinosa x 200-30	79.67[bc]
B. spinosa x 200-60	82.46[c]

Means denoted by the same letter(s) are not significantly different according to Tukey's HSD post hoc test.

HSD indicated no significant difference in exposure duration for either treatment, it revealed three distinct groups, with the control group as the most hydrophilic. The latter showed a significant increase in contact angle at 175°C, and further substantial increase with intensified temperature exposure at 200°C. The same observations were documented in studies on thermal modification of bamboo using other types of oil as treatment medium (Li et al. 2015, Tang et al. 2019b, 2022, Hao et al. 2021).

The interaction between species indicated that under untreated conditions, *B. spinosa* had a more hydrophobic surface than *D. asper*, but the difference was not statistically significant (Table 6). At 175°C exposure, although a relative increase in contact angle was observed for both species, *D. asper* exhibited no significant change relative to the control, while *B. spinosa* showed a more pronounced increase. The duration was observed to have little or no effect on either species. At 200°C, *D. asper's* hydrophobicity increased significantly compared to both the control and 175°C exposure, whereas *B. spinosa* showed significant changes in hydrophobicity at 30 min relative to the control and at 60 min relative to both the control and 175°C exposure. Overall, SCOHT was effective in enhancing the hydrophobic properties of both bamboo surfaces, with *B. spinosa* consistently demonstrating a more hydrophobic surface across all treatment classes. While both species displayed similar responses to increased temperature and prolonged exposure, *B. spinosa* showed more statistically distinct increases across treatment classes.

The observed increase in contact angle across all heat-treated groups indicates that SCOHT effectively enhances the bamboo surface's water repellency (hydrophobicity). This can be attributed to the surface-level chemical modification during the heating process, potentially reducing the number of hydroxyl groups (OH groups) interacting with the water molecules. Oil-heat treatment allows the anhydride functional group in the oil to interact with the hydroxyl groups of hemicellulose via hydrogen bonding or esterification. This leads to the residual oil forming a thin layer of oil on the bamboo surface which acts as a barrier against water droplet penetration, resulting in a higher contact angle (Li et al. 2015). This is also supported by Hao et al.'s (2021) findings from their comparison of atomic force microscopy between untreated and oil-heat-treated sample surfaces, which showed a height difference of 350 nm attributed to the formation of an oil membrane layer on the surface.

The effect of SCOHT on bamboo directly impacts adhesive performance in e-bamboo production. The hydrophobic surface induced by the treatment indicates lower surface energy, which can inhibit adhesive penetration and lead to weaker bonds. With intensified temperature resulting in a more hydrophobized surface, moderate temperature (175°C) is considered the optimal treatment exposure to achieve dimensional stability improvements without much compromise in the surface energy. Further measures to address the reduced wettability due to SCOHT include surface modification techniques to restore surface energy and selection of adhesives that can perform better on hydrophobic surfaces, such as polyurethane and phenol formaldehyde, to name a few (Jimenez & Ramos 2023).

Flexural Strength

The static bending test determined the bamboo's MOR and MOE or its stiffness and resistance to bending-induced deformation, respectively. ANOVA results (Table 7) revealed a statistically significant effect of only the bamboo species for both parameters. Interestingly, treatment and interactions were found to have no significant effects.

B. spinosa appeared to be mechanically stronger than *D. asper* in terms of bending behaviour, with MOR and MOE higher by 17% and 26% on the average, respectively. This can be attributed to variations in their inherent anatomical properties. B. *spinosa* may have a denser cell wall structure with a higher cellulose content than *D. asper*. Cellulose fibres are the primary load-bearing components in bamboo, and their abundance contributes to increased strength and stiffness.

Despite the nonsignificant differences among treatment classes, SCOHT was still observed to weaken the MOR of treated bamboo with a 4%-5% reduction at 175°C and a more pronounced reduction of 16%-23% at intensified temperature of 200°C (Table 8). Similar reductions were also reported by Manalo & Acda (2009) in their

Table 7 ANOVA on the modulus of rupture (MOR) and modulus of elasticity (MOE) of oil-heat-treated *D. asper* and *B. spinosa*

Sources of Variation	Degrees of Freedom	MOR		MOE	
		F-value	*p*-value	F-value	*p*-value
Species (S)	1	5.208	0.028*	36.22	<0.001**
Treatment (T)	4	1.377	0.259^{ns}	1.95	0.121^{ns}
S x T	4	1.814	0.145^{ns}	0.34	0.849^{ns}

** statistically significant at the 1% level
* statistically significant at the 5% level
ns - not statistically significant

Table 8 Mean MOR and MOE of oil-heat treated *D. asper* and *B. spinosa* with treatment classes as a source of variation

Treatment Class	MOR (MPa)	MOE (GPa)
Control	148.95 *(11.59)* ^{a}	12.59 *(1.09)* ^{a}
175-30	141.76 *(11.02)* ^{a}	14.74 *(0.77)* ^{a}
175-60	143.48 *(17.07)* ^{a}	14.74 *(1.05)* ^{a}
200-30	114.53 *(11.98)* ^{a}	13.37 *(1.29)* ^{a}
200-60	125.63 *(13.25)* ^{a}	15.25 *(0.95)* ^{a}

Letters indicate Tukey's HSD grouping; treatment classes with the same letter(s) are not significantly different at the 1% level

study on oil-heat treatment of three Philippine bamboos using virgin coconut oil, although their observed reductions differed significantly.

Other oil-heat treatment investigations for bamboo (Yang et al. 2016, Tang et al. 2019a, Jimenez & Ramos 2024) showed improvement in MOR for temperature exposures up to 180°C, then weakened at exposures beyond this level. This is attributed to bamboo's heat-resistant components, particularly crystalline cellulose and amorphous lignin, both of which provide good mechanical strength. Lignin content tends to increase due to condensation and cross-link mechanisms during the treatment, while cellulose crystallinity rises due to hemicellulose degradation and reorganization of cellulose in the amorphous regions (Tang et al. 2019a).

The present research results showed slight deviations from previous findings, likely due to the bamboo samples within the heating system experiencing higher internal temperatures than indicated by the thermometer used in monitoring. Charred portions were observed on some of the treated poles, which were likely positioned at the bottom of the vat, and in direct contact with the hot plate. Although the charred portions were removed after splitting and discarded as testing specimens, the remaining samples from these poles might have had weakened mechanical properties, which potentially affected the average MOR values. Nevertheless, the results suggest the feasibility of using spent cooking oil as a treatment medium based on the MOR showing no significant changes compared to the control.

Meanwhile, despite being nonsignificant, MOE of oil-heat treated bamboo displayed an improvement of 6% to 21% relative to the control (Table 8). Tang et al. (2019a) and Hao et al. (2021) also observed significant improvements in their treatment of moso bamboo using methyl silicone oil and tung oil, respectively. This shows that SCOHT imparts enhanced resistance to permanent deformation from bending force. Dimensional stability, being positively correlated with MOE, is supported by studies that recorded improved TS and WA at increasing temperature levels (Zhang et al. 2013, Hao et al. 2021). Moreover, the improvement in MOE can be due to increased rigidity and plasticity of bamboo, which can be attributed to moisture loss in the amorphous region of cellulose within the fiber saturation point that allows firm binding of cellulose molecules (Zhang et al. 2013, Hao et al. 2021).

CONCLUSION

This study investigated the effects of SCOHT on the physical and mechanical properties of *D. asper* and *B. spinosa*. The SCOHT process reduced both bamboo species' RD, thickness swelling, and water absorption. This indicates that the treatment improves bamboo's dimensional stability and water resistance and can be utilized with added value.

The SCOHT also significantly increased the contact angle, indicating an enhanced hydrophobic surface for both bamboo species. The decrease in hydrophilicity significantly affects adhesion, thus selecting a suitable adhesive is necessary when working with oil-heat-treated bamboo.

Regarding mechanical properties, the SCOHT, within the parameters used in this study, did not significantly affect bamboo species' MOR and MOE. This suggests that the treatment may not have a detrimental impact on the bending strength and stiffness of bamboo at moderate temperatures and durations.

The observed differences in all properties between *D. asper* and *B. spinosa* can be attributed to their inherent anatomical structure and cell wall composition variations. *B. spinosa* displayed naturally higher RD, lower thickness swelling, lower water absorption, higher MOR, and higher MOE than *D. asper*.

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