ACS OMEGA
Open Access

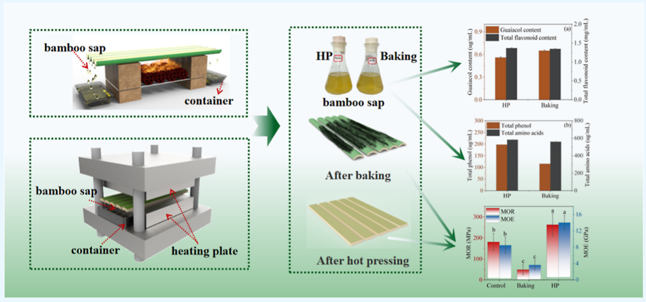
http://pubs.acs.org/journal/acsodf
Article

Extraction of Bamboo Sap by High-Efficiency Hot Pressing: A Method for High Value and Sustainable Use of the Bamboo Material

Fen Chen, Aokai Cheng, Jianping Xiang, Xianju Wang, Litao Guan, Xiuyi Lin,* and Dengyun Tu*

Cite This: *ACS Omega* 2025, 10, 7362−7370
Read Online

ABSTRACT: To develop an effective and eco-friendly method for extracting bamboo sap can effectively improve the utilization of bamboo resources and promote the sustainable development of the bamboo industry. In this work, fresh bamboo strips were directly placed into a hot press for hot pressing (HP), yielding both pure bamboo sap and flattened, dense bamboo strips. The physicochemical properties of bamboo sap and bamboo strips were systematically investigated. The results indicated that the HP method offers significant advantages in terms of the bamboo sap extraction efficiency and the mechanical properties of bamboo. The bamboo sap extracted through HP exhibited a guaiacol concentration comparable to that obtained via the traditional baking method, while the levels of total flavonoids, amino acids, and total phenols were notably higher. The density distribution of the hot-pressed bamboo strips was uniform with a bending strength of 263 MPa and a modulus of elasticity of 14.04 GPa, reflecting enhancements of 45.30% and 65.17%, respectively. Furthermore, the hot-pressed bamboo demonstrates excellent dimensional stability, thereby expanding its potential applications in construction and furniture. The HP method achieves the simultaneous extraction of bamboo sap and the physical modification of bamboo strips, significantly improving resource utilization efficiency, minimizing waste, and simplifying the steps involved in traditional methods, ultimately showcasing considerable environmental benefits.



1. INTRODUCTION

Bamboo, one of the planet's fastest-growing and oldest plants, is increasingly regarded as a sustainable and renewable biomass resource[1−3] and has applications across a broad range of industries, including construction, transportation, furniture, chemicals, energy, and medicine.[4−6]

Bamboo sap is a high-value natural product derived from bamboo resources, rich in amino acids, flavonoids, and polyphenols, which confer significant antioxidant properties, effectively scavenging free radicals, enhancing immunity, and promoting skin wound healing. Additionally, the amino acids and trace elements present in bamboo sap can stimulate cellular activity and improve skin health.[7−9] The nutrient-rich composition of bamboo sap makes it suitable for beverage production and demonstrates substantial medicinal potential across various fields, including food, cosmetics, and medicine.[10,11] By conducting in-depth research and development on bamboo sap, the bamboo industry can be infused with new vitality and economic potential. Currently, bamboo sap production relies on traditional baking and distillation methods, which are resource-intensive and complex, hindering sustainable production. In addition, the process of extracting bamboo sap destroys the structure of the bamboo material, which poses a challenge to its subsequent utilization of the bamboo material.

On the other hand, as living standards rise, the demand for wood products has increased significantly, creating a supply demand imbalance. Bamboo, with its excellent mechanical properties, is becoming a popular alternative to wood. There are two main ways to use bamboo: one is the direct application of round bamboo for construction and furniture, while the other involves processing bamboo into smaller components, such as strips, fibers, and bundles that are glued into panels.[12−15] However, this method not only leads to resource wastage but also demands a significant amount of adhesive, thereby increasing production costs. In addition, current bamboo processing techniques overlook the potential of bamboo sap, which results in further waste. Thus, it is crucial to develop more efficient and eco-friendly methods for extracting bamboo sap by integrating this process with traditional bamboo manufacturing to create a holistic approach that enhances the sustainable and high-quality use of bamboo resources.

Received: December 12, 2024
Revised: February 5, 2025
Accepted: February 7, 2025
Published: February 14, 2025

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370

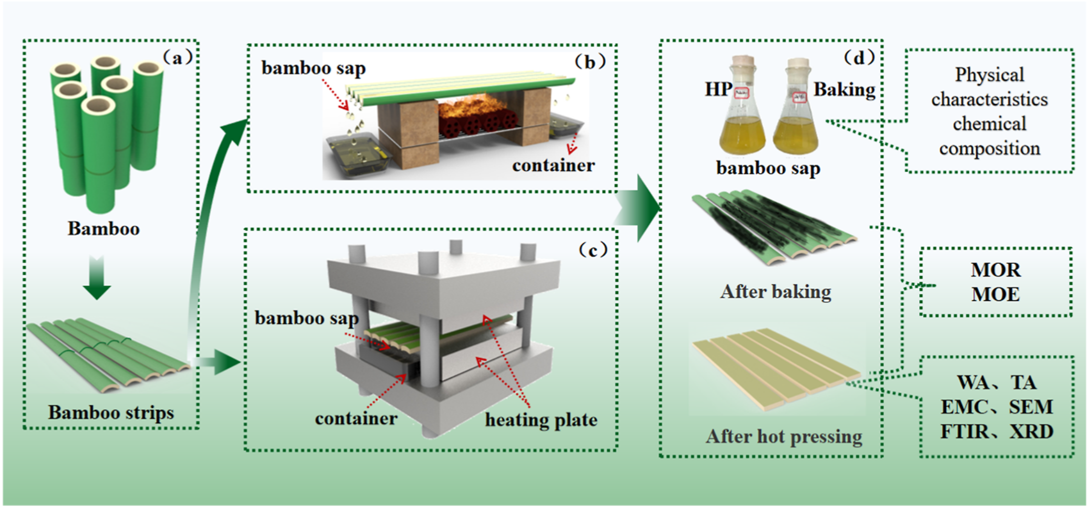


Figure 1. Bamboo sap extraction and bamboo HP process. (a) Bamboo; extraction of bamboo sap by baking (b) and HP (c); (d) bamboo sap and bamboo strips by baking and HP.

Hot pressing (HP) is a physical technique used to alter the structure and properties of bamboo by increasing its density and strength.[16−18] HP densifies the bamboo and increases the concentration of vascular bundles per unit area, which enhances the bamboo density and strength. The chemical composition of the cell walls also changes during the HP, including a reduction in the hydroxyl groups and an increase in crystallinity.[19−22] These changes contribute to improved mechanical characteristics. Furthermore, the HP method simultaneously dries and flattens bamboo, thereby simplifying the fabrication processing, which in turn improves the utilization efficiency of the bamboo material. During the compression process, a gradient in the moisture content (MC) and water vapor partial pressure can develop within the bamboo. As a result of these temperature and MC gradients, water was rapidly expelled from the bamboo disc,[23−26] and bamboo sap also can be swiftly extracted along the water. Through optimizing the temperature and pressure, HP can serve as an effective technique for bamboo sap extraction and bamboo strip flattening. Hence, in-depth research on HP is required to understand the effects of bamboo sap extraction on bamboo properties. Research and development on bamboo sap could also generate new opportunities and economic benefits for the bamboo industry. There has yet to be any reported research focusing on the extraction of bamboo sap via the HP method.

Therefore, this study applies HP to produce bamboo sap and a high-performance flattened bamboo strip simultaneously. The physicochemical properties of the bamboo sap produced are evaluated, and the chemical and mechanical properties of bamboo strips after HP are systematically investigated. Hot-pressing has been proven to be efficient, simple, and environmentally friendly in the comprehensive utilization of bamboo. This approach offers a novel strategy for the effective and sustainable use of bamboo resources.

2. MATERIALS AND METHODS

2.1. Materials. Fresh Moso bamboo, 4−5 years old, felled in March (Shaoguan, Guangdong, Renhua County), 70%−80% water content. The bamboo timber was sawn into 400 mm long tubes and dissected into bamboo strips with a width of 25−30 mm for spare use (Figure 1a). Analytical grade guaiacol, rutin, and leucine were purchased from Biotopped Co., Ltd.

2.2. Bamboo Sap Extraction. *2.2.1. Baking Method.* Fresh bamboo sticks were cut into strips measuring 380−400 mm (length) × 25−30 mm (width) × 8−10 mm (thickness) and inserted into a press measuring 300 × 300 mm. Then, the bamboo strips were placed over the coals, and the containers were positioned on both sides of the bamboo strips to collect the extracted bamboo sap until no more liquid was released (Figure 1b).

2.2.2. Hot Pressing Method. Fresh bamboo sticks were cut into strips measuring 380−400 mm (length) × 25−30 mm (width) × 8−10 mm (thickness) and inserted into a press measuring 300 × 300 mm. They were subjected to HP at a temperature of 180 °C and a pressure of 0.1 MPa for 15 min. The containers were positioned on both sides of the bamboo strips to collect the extracted bamboo sap (Figure 1c). And the hot-pressed bamboo strips were called as "HP", and the untreated bamboo strips were referred to as "control".

2.3. Characterization of the Bamboo Sap. *2.3.1. Physical Characteristics.* The pH value of the bamboo sap was tested using a pH meter (LC23014053, Shanghai LI-CHEN Bang Xi Instrument Technology Co., Ltd.), the relative density value of the bamboo sap was determined according to standard GB 5009.2-2024, and each sample was tested 3 times.

The bamboo sap (25 mL) was accurately measured, placed in a constant-weight evaporation dish, completely evaporated in a water bath, and dried in an oven at 105 °C for 5 h. The solid content (TSC) was calculated using eq 1

$$\mathrm{TSC} = \frac{m_1 - m_2}{m_1} \times 100\% \tag{1}$$

m_1 is the mass of the bamboo sap before evaporation and m_2 is the solid mass of the bamboo sap after drying.

2.3.2. Chemical Composition of the Bamboo Sap. Guaiacol was analyzed following the methodology outlined by Li and Jiang.[27] High-performance liquid chromatography (Agilent InfinityLab Poroshell 120 SB-C18) was employed to determine the guaiacol content in the bamboo sap. A standard curve (R^2 = 0.9997) was established using methanol solutions of guaiacol at concentrations ranging from 20 μg/mL to 100 μg/mL for quantification purposes.

The total flavonoid content of the bamboo sap was determined using ultraviolet−visible (UV−vis) spectroscopy

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370

(Evolution 201, Thermo Fisher Scientific).[28] Quantification of total flavonoid content was achieved by plotting a standard curve (R^2 = 0.9981) using rutin solutions at concentrations ranging from 0.7 to 3.6 mg/mL. Total flavonoid content was expressed as mg of rutin per mL of bamboo sap.

The total phenolic content was assessed using a traditional method.[29] An ultraviolet spectrophotometer was utilized, measuring the absorbance at 220 nm with methanol serving as the blank control solution. A standard curve was created with methanol solutions of guaiacol at concentrations of 3−20 μg/mL (R^2 = 0.9959) to quantify the total phenolic content in bamboo sap.

The amino acid content of the bamboo sap was quantified using the indotrione colorimetric method,[29] with a standard curve established using leucine solutions at concentrations ranging from 8 to 32 μg/mL (R^2 = 0.9973). Amino acid content was expressed as μg of leucine per mL of bamboo sap.

2.4. Characterization of Bamboo Strips. *2.4.1. Chemical Structure of Bamboo.* The chemical functional groups of the bamboo strips were analyzed by Fourier transform infrared (FTIR) spectroscopy (TENSOR27, Bruker) with a scanning wavenumber range of 500−4000 cm^{-1}. Bamboo strips were ground into powder, mixed with KBr, and compressed into thin flakes for measurement.

The crystallinity of the control and HP samples was investigated using an X-ray diffractometer (ULTIMAIV, Rigaku) equipped with a Cu Kα radiation source (λ = 0.154 nm) operating at 40 kV and 100 mA. The scanning range was 5° ≤ 2θ ≤ 45°, with a scanning speed of 10° min^{-1}. The calculation was performed according to the Segal equation for crystallinity, using eq 2

$$C_I = \frac{I_{002} – I_{am}}{I_{002}} \times 100\% \tag{2}$$

where C_I is the relative crystallinity (%), I_{002} is the diffraction intensity of the 002 crystalline plane (2θ = 22.2°), and I_{am} is the diffraction intensity of the amorphous region (2θ = 18.0°).

2.4.2. Microstructure and Density. Scanning electron microscopy (SEM) (Sigma 300, Zeiss) was employed to examine the cellular structure of the control and HP samples, with each sample measuring 5 mm (length) × 5 mm (width) × 5 mm (thickness).

2.4.3. Density Profile. The density distribution curves of the control and HP samples were determined by using an X-ray profile density distribution tester (DPX-300LTE, IMAL), with the scanning step along the thickness direction of the bamboo set at 0.05 mm. The specimens used for the profile density test had dimensions of 50 mm (length) × 20 mm (width) × t mm (thickness). A total of ten specimens were tested in this study.

2.4.4. Dimensional Stability and Water Absorption (WA) of Bamboo. The control and HP samples were processed into specimens with dimensions of 20 mm × 20 mm. The initial thickness of the dry specimens was measured and recorded as t_0. The specimens were completely immersed in water and soaked for 24 h. After this period, the specimens were removed, and the thickness was measured and recorded as t_1. The water-absorbing thickness was calculated using eq 3

$$WAT = \frac{t_1 - t_0}{t_0} \times 100\% \tag{3}$$

For the WA test, specimens with dimensions of 20 mm × 20 mm × t mm (length × width × thickness) were utilized. The masses of the specimens were recorded after they were dried in an oven and subsequently submerged in water at 20 °C. The mass of the specimens was recorded after immersion periods of 6, 24, 48, 96, and 192 h, respectively. The WA was calculated using eq 4.

$$WA = \frac{m_2 - m_1}{m_1} \times 100\% \tag{4}$$

where m_1 represents the absolute dry mass and m_2 denotes the mass after immersion.

The dimensional stability of bamboo timber was assessed following the extraction of bamboo sap through HP. A sample size of 50 mm (length) × 30 mm (width) × t mm (thickness) was employed. Warpage measurement was conducted in accordance with GB/T 15036.2-2018, and the warpage (f_w) was calculated by using eq 5.

$$f_w = \frac{h_{max}}{w} \times 100\% \tag{5}$$

h_{wax} is the maximum chord height in mm; w is the width of the bamboo strips in mm.

The control and HP samples were measured to have dimensions of 20 mm (length) × 20 mm (width) × t mm (thickness). All samples were stored in a controlled environment chamber maintained at 20 ± 2 °C and 65 ± 5% relative humidity for a duration of 8 days. A total of 15 samples were collected from each group. The equilibrium moisture content (EMC) was determined using eq 6

$$EMC = \frac{m_1 - m_0}{m_0} \times 100\% \tag{6}$$

where m_1 represents the equilibrated mass and m_0 denotes the adiabatic mass.

2.4.5. Mechanical Properties. The mechanical properties and modulus of elasticity were measured after extraction of the bamboo sap by the material, baking method, and hot-pressing method in the three-point bending mode, according to the GB/T 15780-1995 standard. The samples were 160 mm in length, 10 mm in width, and t mm in thickness. Fifteen samples were replicated for each group.

2.5. Statistical Analysis. Independent samples t-test, one-way analysis of variance, and Duncan's multiple test were performed using SPSS software to analyze significant differences between factors. The p-value level of statistical significance was $P < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Physical Characteristics of the Bamboo Sap. Table 1 depicts the physical characteristics of the bamboo sap extracted through baking and HP methods. The independent sample t-test for the physical properties of the bamboo sap obtained from both the baked and hot-pressed methods was conducted using SPSS software. The analysis revealed no

Table 1. Physical Characteristics of the Bamboo Sap

method	extraction amount (g/kg)	pH	total solid content (%)	relative density
baking	44.66 ± 5[a]	5.51 ± 0.1	1.9 ± 0.1	1.012 ± 0.01
hot pressing	52.81 ± 8[a]	5.46 ± 0.1	2.2 ± 0.2	1.011 ± 0.01

[a]Represents significant difference, $p < 0.05$.

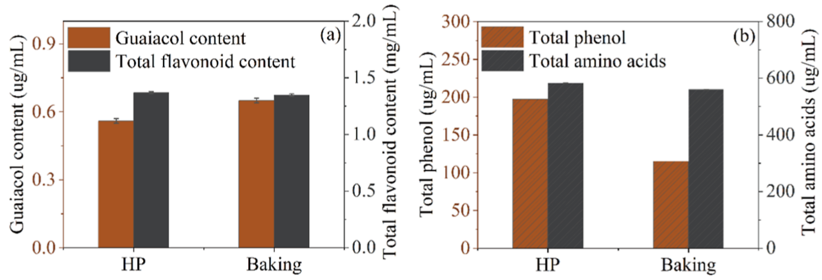


Figure 2. Chemical composition of the bamboo sap. (a) Guaiacol and total flavonoid content; (b) total phenol and total amino acid content.

Table 2. Identification of the GC−MS Components of the Bamboo Sap Extracted by Baking and the HP Method

no.	T_r/min	component	molecular formula	molecular mass	relative percent %	
					baking	HP
1	6.318	cyclohexanone	$C_6H_{10}O$	98.14	2.09	2.85
2	6.68	3-methylstyrene	C_9H_{10}	118.18	0.28	0.2
3	7.242	hydroxyacetone	$C_3H_6O_2$	74.08	4.04	
4	8.153	1-nonanal	$C_9H_{18}O$	142.24		0.1
5	9.029	acetic acid	$C_2H_4O_2$	60.05	14.99	1.57
6	9.193	methylglyoxal	$C_3H_4O_2$	72.06		0.3
7	10.274	pyrrole	C_4H_5N	67.09		2.36
8	10.746	2,3-dihydro-3,5-dihydroxy-6-methyl-4(*H*)-pyran-4-one	$C_6H_8O_4$	144.13	0.48	
9	11.472	5-methyl furfural	$C_6H_6O_2$	110.11	0.35	
10	11.659	4-cyclopentene-1,3-dione	$C_5H_4O_2$	96.08	0.38	
11	13.169	furfuryl alcohol	$C_5H_6O_2$	98.1	1.82	
12	14.293	(5-methyl-2-furyl)methanol	$C_6H_8O_2$	112.13	0.30	
13	14.825	2(5*H*)-furanone	$C_4H_4O_2$	84.07	0.25	
14	15.386	methyl salicylate	$C_8H_8O_3$	152.15		0.1
15	16.190	methyl cyclopentenolone	$C_6H_8O_2$	112.13	0.23	
16	17.973	acrylamide	C_3H_5NO	71.08	0.23	
17	18.867	2*H*-pyran-2,6(3*H*)-dione	$C_5H_4O_3$	112.08	0.38	
18	19.604	furaneol	$C_6H_8O_3$	128.13	0.98	
19	20.408	2,5-dihydroxy-1,4-dioxane-2,5-dimethanol	$C_6H_{12}O_6$	180.16	6.56	3.64
20	22.503	methyl 14-methylpentadecanoate	$C_{17}H_{34}O_2$	270.45		0.39
21	22.776	2,3-dihydro-3,5-dihydroxy-6-methyl-4(*H*)-pyran-4-one	$C_6H_8O_4$	144.13	2.78	
22	22.981	4*H*-pyran-4-one,3,5-dihydroxy-2-methyl-	$C_6H_6O_4$	142.11	0.56	
23	23.743	2,3-dihydrobenzofuran	C_8H_8O	120.15	5.35	20.37
24	24.462	5-hydroxymethylfurfural	$C_6H_6O_3$	126.11	5.9	2.66
25	24.521	benzo[*b*]thiophene-3-carboxaldehyde,2-(methylseleno)-	$C_{10}H_8OSSe$	255.19		0.49
26	24.751	1,3-propanediol,2-(1,4,7,10,13,16-hexaoxacyclononadec-18-yl)-	$C_{16}H_{32}O_8$	352.42		0.39
27	24.855	vanillin	$C_8H_8O_3$	152.15	1.16	1.77
28	25.083	hexaethylene glycol	$C_{12}H_{26}O_7$	282.33		2.17
29	25.149	18,18′-bi-1,4,7,10,13,16-hexaoxacyclononadecane	$C_{26}H_{50}O_{12}$	554.67		0.98
30	25.180	C12E8	$C_{28}H_{58}O_9$	538.75		5.61
31	25.265				4.95	
32	25.592	dibutyl phthalate	$C_{16}H_{22}O_4$	278.34	5.4	10.43
33	26.666	3-hydroxybenzaldehyde	$C_7H_6O_2$	122.12		11.71
34	27.150	1,4,7,10-tetraoxacyclotridecane,12,12′-(1-methylethylidene)bis-	$C_{21}H_{40}O_8$	420.54	3.30	
35	30.339	octoxynol-5	$C_{24}H_{42}O_6$	426.59		1.67
36	30.359	erucamide	$C_{22}H_{43}NO$	337.58	23.95	

significant differences in any of the physical properties, with the exception of the amount of extraction.

The colors of the bamboo sap extracted using both methods are similar, displaying a pale yellow tint. Variations in the temperature and water content gradients under the applied temperature and pressure facilitated the rapid drainage of the bamboo sap. The quantity of bamboo sap extracted via the HP method was greater than that obtained via the baking method. A maximum of 52.81 g/kg of the bamboo sap by the HP method and 44.66 g by the baking method is obtained. The relative density and total solids content of the bamboo sap complied with the *Ministry of Health Drug Standard for Traditional Chinese Medicines, Volume 1* regulatory standards, with values being slightly higher for the bamboo sap obtained through HP compared to those obtained through baking. The pH values of the bamboo sap from both methods were similar. A comparison of the basic characteristics of the bamboo sap indicated that the samples obtained by both baking and HP were comparable, and the extraction efficiency of the hot-pressing method was higher than that of the baking method.

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370

Table 3. Phenolic Acids in Bamboo Sap

no.	T_r/min	component	molecular formula	molecular mass	relative percent %	
					baking	HP
1	10.233	formic acid	CH_2O_2	46.03	4.09	0.2
2	10.922	propionic acid	$C_3H_6O_2$	74.08	0.43	
3	16.716	guaiacol	$C_7H_8O_2$	124.14	0.4	0.3
4	19.109	phenol	C_6H_6O	94.11	0.73	0.49
5	22.039	4-hydroxy-3-methoxystyrene	$C_9H_{10}O_2$	150.17	1.99	2.07
7	23.465	(*E*)-2-methoxy-4-(prop-1-enyl)phenol	$C_{10}H_{12}O_2$	164.2	0.13	0.98
8	27.149	3,4,5-trimethoxyphenol	$C_9H_{12}O_4$	184.19		8.66
9	28.479	ethoxyphenol	$C_8H_{10}O_2$	138.16		17.52

3.2. Quantitative Analysis of the Chemical Composition of the Bamboo Sap. Figure 2a shows the guaiacol and total flavonoid contents of the bamboo sap obtained by different methods. Guaiacol, the primary active compound in bamboo sap, is known for its expectorant and cough-suppressing effects, as well as its antibacterial and anti-inflammatory properties, which help reduce respiratory secretions.[30,31] A quantitative assessment of guaiacol in the bamboo sap extracted via the baking method and HP revealed no significant difference, with concentrations of 0.65 μg/mL for the baking method and 0.56 μg/mL for HP (Figure 2a). Bamboo sap also contains flavonoids that provide antioxidant, antimicrobial, and immunity-regulating benefits.[32−34] The quantitative analysis showed that the total flavonoid content in the bamboo sap obtained through HP was slightly higher, measuring 1.348 mg/mL for the baking method and 1.369 mg/mL for the HP.

Figure 2b shows the total phenol and amino acid contents of the bamboo sap. The bamboo sap extracted using the baking method had amino acid and total phenol concentrations of 560.31 and 114.98 μg/mL, respectively. In contrast, the HP method yielded higher amino acid and total phenol contents, at 582.88 and 197.45 μg/mL, respectively, representing increases of 4.02% and 71.72% compared to the baking method. GC−MS analysis (Tables 2 and 3) also indicates a higher concentration of phenolic compounds in the bamboo sap obtained by HP. The significant increase in total phenol content can be attributed to the degradation of bamboo cells under high temperatures and pressure. Additionally, the high pressure accelerates chemical reactions, enhancing the transformation and stability of certain phenolic compounds, which improves the extraction efficiency of total phenols.[35−37]

The above analysis of the chemical content of the bamboo sap demonstrated that HP is an efficient extraction method. Compared to the baking method, HP is easier to operate and better suited to continuous production in the industry.

3.3. Bamboo Chemical Composition Analysis. The FTIR spectra of the control and HP are presented in Figure 3a.

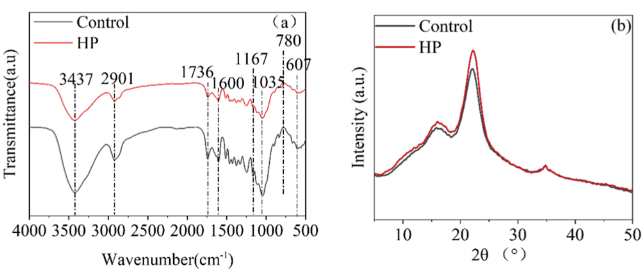


Figure 3. Chemical composition of control and HP. (a) FTIR, (b) XRD.

The peak observed at 3437 cm^{-1} corresponds to the stretching vibration of the hydroxyl group (−OH). The absorption region from 3000 to 2750 cm^{-1} is attributed to the stretching vibration of the methylene group. Additionally, the region between 1800 and 1580 cm^{-1} is primarily associated with the stretching vibration of the carbonyl group (−C═O) found in ketones, aldehydes, carboxylic acids, and esters present in cellulose and hemicellulose. The peak at 1600 cm^{-1} signifies the stretching vibration of the benzene ring skeleton. Finally, the peak at 1167 cm^{-1} is indicative of the stretching vibration of the thermocycler inner ether (−C−O−C−).

As illustrated in Figure 3a, the spectra of both samples exhibit the typical characteristics of bamboo; however, the intensities of the characteristic peaks differ. The intensity of the peaks at 3437 and 1640 cm^{-1} is higher in the control, suggesting a more significant presence of the O−H and C═O functional groups, which may indicate enhanced WA capabilities. After HP, the peak intensity at 3437 cm^{-1} was significantly reduced, indicating a decrease in the content of the hydroxyl groups. This reduction may be attributed to the condensation reactions between free hydroxyl groups and adjacent cellulose chains under high temperatures and pressures, removing water molecules and forming ether bonds, which further decreases the number of free hydroxyl groups. The poor thermal stability of hemicellulose, along with the ease of hydrolysis of its acetyl groups to form acetic acid at elevated temperatures, has contributed to a reduction in the number of carbonyl groups. Furthermore, under acidic conditions, the chemical reaction of lignin led to a further decrease in hydroxyl groups and a slight increase in carbonyl groups, significantly diminishing the number of hydrophilic groups. Consequently, this modification enhances the dimensional stability of the hot-pressed lumber and reduces the EMC.[38,39] It is noteworthy that the mechanical properties of bamboo are typically inversely proportional to the MC below the saturation point of the fibers.[40] Therefore, reducing the number of hydrophilic groups may enhance the mechanical properties of bamboo.

Figure 3b illustrates the changes in the crystallinity of bamboo strips after HP. Crystallinity significantly influences the mechanical properties of bamboo; higher crystallinity indicates a denser and better aligned cellulose molecule, which enhances the mechanical characteristics of the material. However, this increase in crystallinity also affects bamboo's WA and dimensional stability to some extent.[41,42] Figure 3b clearly shows the distinction in the intensity of the crystal diffraction peaks of the control and HP. The calculated crystallinity of HP is greater than that of the control samples, with values of 45.97% for (HP) and 42.63% for the control. These findings agree with Kadivar, suggesting that at elevated temperatures, bamboo undergoes several chemical reactions, including thermal degradation and

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370

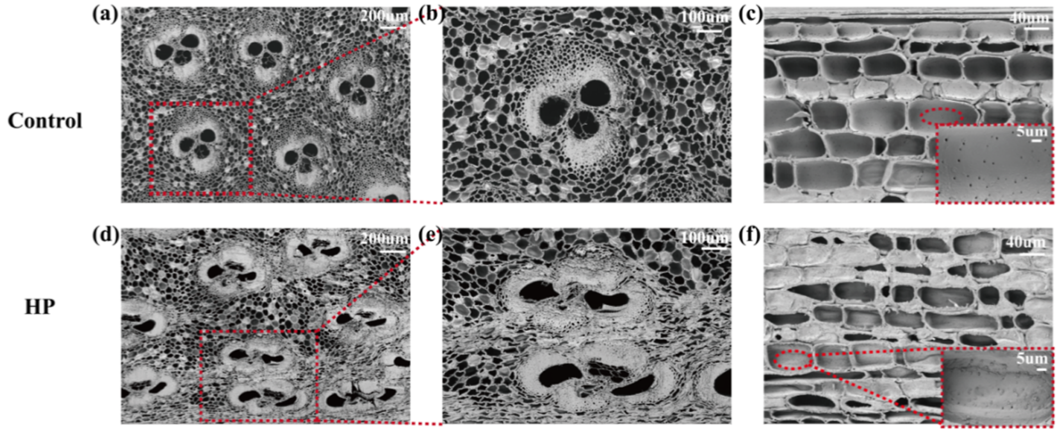


Figure 4. Microscopic morphology of control (a−c) and HP (d−f).

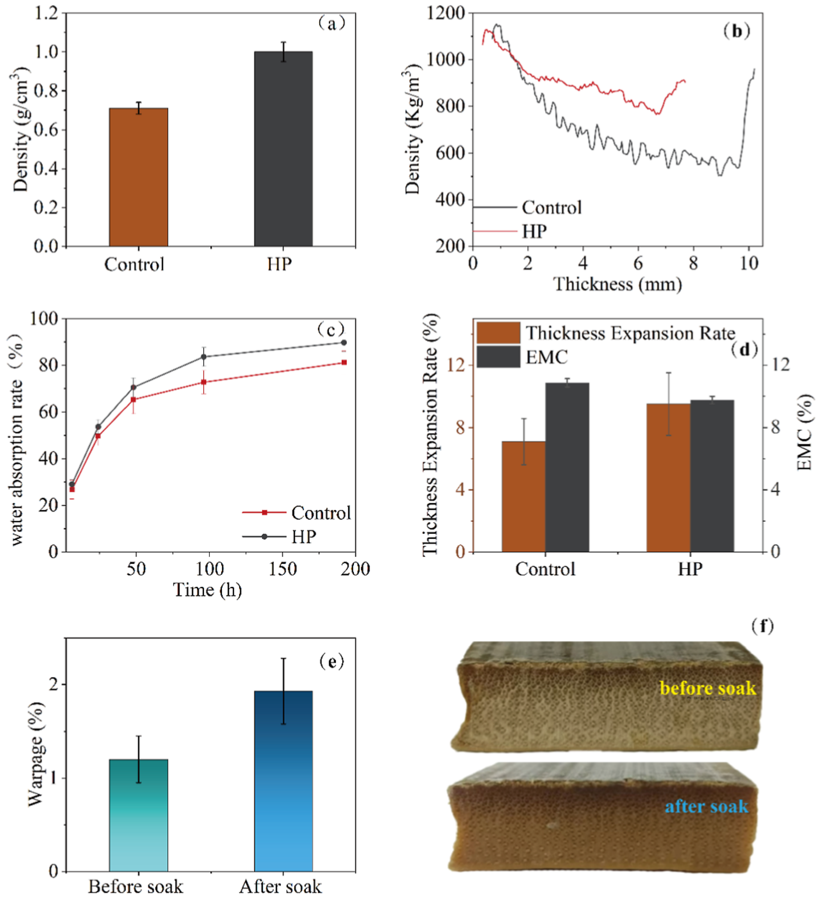


Figure 5. Physical properties of bamboo: (a) density, (b) profile density, (c) WA, (d) EMC and absorption thickness expansion, (e) warpage of the hot-pressed material, and (f) physical drawing of HP after soaking in water for 48 h.

condensation, that can lead to changes in the crystallinity and chemical composition.[43,44] The results of XRD were consistent with those in FTIR.

3.4. Morphology and Microstructure of Bamboo. The SEM images of the control and HP are presented in Figure 4. No deformation or displacement of the vascular bundles was observed in the control, and the parenchyma cells appeared clear and rounded, with the striated holes in the cell walls remaining visible (Figure 4a−c). However, it was evident that the vascular bundles underwent deformation due to the pressure exerted on the bamboo during the hot pressings and parenchyma cells were compressed (Figure 4d−f). The disparity in the dimensions of the inner and outer diameters of the bamboo inevitably leads to inner stretching and outer compression and flattens the bamboo. The compression of the cells increases the density of the bamboo strips to a certain extent, thereby enhancing the mechanical properties.

3.5. Physical Properties of Bamboo. Figure 5 illustrates the density and dimensional stability of bamboo. From Figure 5a,b, it is evident that the density of bamboo increased after HP, attributed to the compression of the vascular bundles and parenchyma cells and the increase of vascular bundles per unit

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370

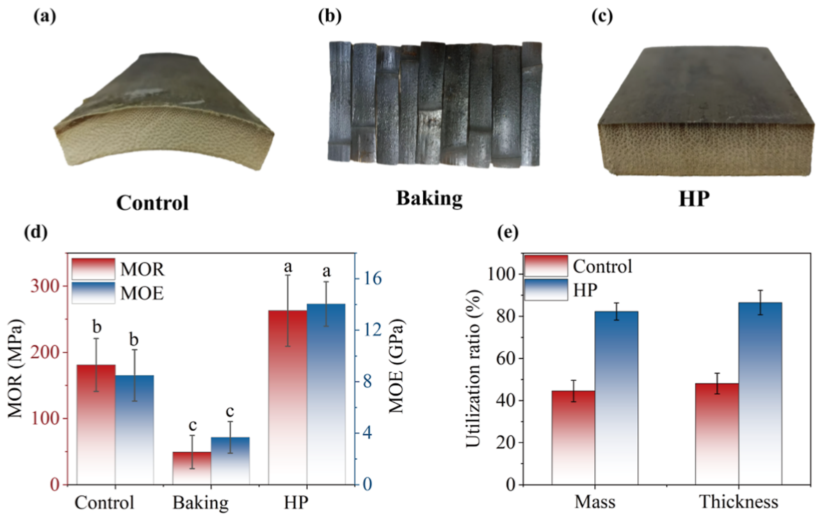


Figure 6. (a) Control; bamboo strips after extraction of the bamboo sap by baking (b) and HP (c); (d) mechanical properties; (e) the utilization ratio of bamboo. Different lowercase letters indicate a significant difference between means ($p < 0.05$). Error bars show standard deviations.

area. Additionally, the density distribution of the bamboo strips became more uniform, which positively impacted their mechanical properties. The WA rate of HP was found to be higher than that of the control (Figure 5c). This phenomenon occurs because mechanical compression significantly reduces the volume of the bamboo cell cavities during HP. As the bamboo cell walls regain their plasticity during WA, they exhibit a tendency to revert to their precompression shape, which may create negative pressure during this reversion process, thereby facilitating WA. The expansion rate of hot-pressed bamboo exceeds that of the control material but remains within acceptable limits. Furthermore, due to the decomposition of hemicellulose and the chemical reactions involving lignin, the EMC of bamboo is reduced after HP, which is 10.87% for the control and 9.75% for HP (Figure 5d). This finding aligns with the results obtained from the FTIR analysis.

Bamboo strips are dried and processed to reduce the MC and minimize warping. As illustrated in Figure 5e,f, the maximum warpage of HP was approximately 1.33%, which is in agreement with Wang; higher HP temperatures decrease both the MC and the warping of the bamboo strips.[45] After 48 h immersion of HP in water, the warping degree of the bamboo strips was measured at 1.92%. The observed warping deformation was minimal, indicating that the hot-pressed material demonstrated good dimensional stability.

3.6. Mechanical Properties.

Figure 6 illustrates the mechanical properties of the control bamboo and the bamboo after extraction of the bamboo sap by the baking and hot-pressing methods. The mechanical properties of the bamboo material extracted using the baking method demonstrated a significant decline, with bending strength decreasing from 181 to 49.27 MPa, indicating a reduction of 72.78%. The modulus of elasticity also decreased from 8.5 to 3.68 GPa, representing a 56.71% reduction. This decline can be attributed to the severe charring of the bamboo skin surface that occurs during sap extraction via the baking method, which damages the surface morphology of the bamboo. Notably, the mechanical strength of bamboo skin is superior to that of the bamboo pith and bamboo flesh; however, the carbonization of the bamboo skin surface adversely affects the overall mechanical strength of the bamboo material. Following the extraction of the bamboo sap by HP, the bamboo strips were subjected to compression at specific temperature and pressure conditions, resulting in an increase in density. The reduction of hydrophilic groups, along with an increase in crystallinity, further enhanced the mechanical strength of the bamboo compared to the control. The bending strength of HP was measured at 263 MPa, and the modulus of elasticity was recorded at 14.04 GPa, representing increases of 45.30% and 65.17%, respectively, compared to the control (181 MPa and 8.5 GPa). Additionally, the HP process flattened the bamboo strips, transforming their shape from curved to rectangular (Figure 6a,b), which facilitates the subsequent processing and utilization of the bamboo materials. Bamboo surface sanding is a meticulous bonding process aimed at preserving the integrity of the bamboo tissue as much as possible. Figure 6d depicts the changes in mass and thickness of the bamboo before and after sanding of the control and HP. After sanding, the mass loss of the control was only 55.46%, and the thickness loss was 51.92%. In contrast, the mass loss of HP was significantly lower at 17.74%, with a thickness loss of 14.66%, resulting in a high utilization rate of 80%. Thus, the processes of HP and flattening not only enhance the convenience of subsequent processing but also substantially improve the utilization rate of the bamboo material.

4. CONCLUSIONS

This study presents an efficient method for extracting high-purity bamboo sap while simultaneously flattening the bamboo. The HP process is rapid, straightforward, environmentally sustainable, and well-suited for continuous industrial use. Bamboo sap produced using HP demonstrates guaiacol concentrations comparable to those obtained through traditional baking methods, along with higher levels of total flavonoids (1.369 mg/mL), amino acids (582.88 μg/mL), and total phenols (197 μg/mL). The hot-pressed bamboo strips exhibit uniform densities, a high flexural strength of 263 MPa, and an elastic modulus of 14.04 GPa while reducing the MC from 70 to 80% to 15−20%. This makes the material ideal for further applications, such as particleboard and finger-jointed boards. The integration of bamboo sap extraction with traditional processing maximizes resource efficiency, minimizes waste, and supports sustainable development, thereby enhancing the profitability and environmental benefits of the bamboo industry.

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370

The findings of this study provide innovative ideas and technical support for sustainable development of the bamboo industry. Through HP technology, not only is the added value of the bamboo material increased, but also efficient extraction of the bamboo sap is achieved, laying the groundwork for its widespread application in the fields of food, cosmetics, and medicine. Furthermore, the improved performance of bamboo wood following HP treatment expands its application potential in construction and furniture, contributing to alleviation of the imbalance between the wood supply and demand.

AUTHOR INFORMATION

Corresponding Authors

Xiuyi Lin − *Key Laboratory of Advanced Materials for Facility Agriculture, Ministry of Agriculture, South China Agricultural University, Guangzhou 510642, China*; Email: lxysandy@scau.edu.cn

Dengyun Tu − *Key Laboratory of Advanced Materials for Facility Agriculture, Ministry of Agriculture, South China Agricultural University, Guangzhou 510642, China*; orcid.org/0000-0001-5704-2170; Email: tudengyun@scau.edu.cn

Authors

Fen Chen − *Key Laboratory of Advanced Materials for Facility Agriculture, Ministry of Agriculture, South China Agricultural University, Guangzhou 510642, China*

Aokai Cheng − *Key Laboratory of Advanced Materials for Facility Agriculture, Ministry of Agriculture, South China Agricultural University, Guangzhou 510642, China*

Jianping Xiang − *Hongwei Wooden Products (Renhua) Company Limited, Shaoguan 512000, China*

Xianju Wang − *Key Laboratory of Advanced Materials for Facility Agriculture, Ministry of Agriculture, South China Agricultural University, Guangzhou 510642, China*

Litao Guan − *Key Laboratory of Advanced Materials for Facility Agriculture, Ministry of Agriculture, South China Agricultural University, Guangzhou 510642, China*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.4c11224

Author Contributions

Fen Chen: Writing—original draft, Investigation, Formal analysis. **Aokai Cheng:** Data curation. **Jianping Xiang:** Investigation, Supervision. **Xianju Wang:** Revised the manuscript. **Litao Guan:** Funding acquisition. **Xiuyi Lin:** Funding acquisition Investigation, Supervision. **Dengyun Tu:** Investigation, Supervision, Project administration.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors are grateful for the financial support from the Guangdong Forestry Science and Innovation Project (grant number 2024KJCX003), Guangdong Basic and Applied Basic Research Foundation (2024A1515012718), Guangdong Provincial Department of Science and Technology, China (project no. 2022A1515010502), Hongwei Wooden Products (Renhua) CO.; LTD Commissioned project (HXKJHT20232483) and (HXKJHT20231793).

REFERENCES

(1) Chen, X.; Jiang, H.; Wang, G.; Wang, J.; Chen, F. Disposable Bamboo Fiber Meal Boxes Characterized by Efficient Preparation, Excellent Performance, and the Potential for Beneficial Degradation. *J. Clean. Prod.* **2024**, *434*, 139973.

(2) Zhao, X.; Ye, H.; Chen, F.; Wang, G. Bamboo as a Substitute for Plastic: Research on the Application Performance and Influencing Mechanism of Bamboo Buttons. *J. Clean. Prod.* **2024**, *446*, 141297.

(3) Hu, J.; Wu, J.; Huang, Y.; He, Y.; Lin, J.; Zhang, Y.; Zhang, Y.; Yu, Y.; Yu, W. Super-Strong Biomimetic Bulk Bamboo-Based Composites by a Neural Network Interfacial Design Strategy. *Chem. Eng. J.* **2023**, *475*, 146435.

(4) Chen, M. L.; Weng, Y.; Semple, K.; Zhang, S.; Hu, Y.; Jiang, X.; Ma, J.; Fei, B.; Dai, C. Sustainability and Innovation of Bamboo Winding Composite Pipe Products. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110976.

(5) Guan, M. J.; Li, Y.; Xu, X.; Fu, R. Anti-Mold and Hydrophobicity of Cutinized Bamboo Prepared via Different Annealing Processes. *Ind. Crops Prod.* **2022**, *187* (PA), 115399.

(6) Guo, W.; Kalali, E. N.; Wang, X.; Xing, W.; Zhang, P.; Song, L.; Hu, Y. Processing Bulk Natural Bamboo into a Strong and Flame-Retardant Composite Material. *Ind. Crops Prod.* **2019**, *138*, 111478.

(7) Li, W.; Sheng, H. Effects of Bamboo Charcoal-Based Bio-Fertilizer on Wine Bamboo Sap Yield and Nutrient Composition. *J. For. Res.* **2018**, *29* (4), 1083−1092.

(8) Gao, Q.; Wang, D.; Shao, S.; Xue, Y.; Zhang, Y.; Chen, C.; Tang, F.; Sun, J.; Li, Y.; Guo, Q. Identification and Quantitation of the Actual Active Components in Bamboo Juice and Its Oral Liquid by NMR and UPLC-Q-TOF-MS. *Sci. Rep.* **2020**, *10* (1), 19664.

(9) Liu, B.; Li, C.; Dai, J.; Xu, J.; Ye, H.; Gong, J.; Zhang, W.; Zeng, Y.; Chu, C. Revealing Chemical Differences and Pharmacological Activities of Succus Bambusae Prepared by Different Methods Using Comparative Metabolomics Integrated Network Pharmacology and Spectrum-Effect Relationship Approach. *Ind. Crops Prod.* **2024**, *222* (P2), 119611.

(10) Huang, X.; Chen, X.; Xian, Y.; Jiang, F. The Material Sources, Pharmacological Activities of Bamboo Polysaccharides and Influencing Factors: A Review. *Ind. Crops Prod.* **2024**, *210*, 118037.

(11) Rui, Z.; Bo, C.; Qingfeng, Z. Comparison of the Chemical Components and Preparation Methods of Bamboo Juice Made from Phyllostachys Heterocycla Cv. Pubescens and Phyllostachys Glauca McClure. *Food Ferment. Ind.* **2020**, *46* (06), 205−211.

(12) Zhao, Y.; Zhang, S.; Liu, M.; Chen, Q.; Zhang, Y.; Huang, Z. X.; Qu, J. P. Multifunctional Bamboo-Based Composites in-Situ Coated with Graphene via Continuous Steam Explosion. *Chem. Eng. J.* **2024**, *484*, 149389.

(13) Liang, E.; Zhou, Q.; Lin, X.; Wang, X.; Li, X.; Ma, H.; Shi, L.; Hu, C.; Tu, D. Feasibility of One-Time Drying for Manufacturing Bamboo Scrimber: Fresh Bamboo Bundle at High Initial Moisture Content Impregnated by PF. *Ind. Crops Prod.* **2023**, *194*, 116302.

(14) Fan, Z.; Xu, S.; Liu, X.; Cao, Q.; Cao, Y.; Wu, X. Aspergillus Niger Infection Weakens the Robustness of Bamboo-Adhesive Interphases by Damaging the Adhesive and Detaching the Interfacial Bonding. *Ind. Crops Prod.* **2023**, *204*, 117402.

(15) Shukla, S. R.; Kelkar, B. U.; Yadav, S. M.; Bijila, A. Studies on Laminated and Scrimber Composites Produced from Thermally Modified D. Strictus Bamboo Bonded with Melamine-Based Adhesive. *Ind. Crops Prod.* **2022**, *188*, 115649.

(16) Li, Z.; Chen, C.; Mi, R.; Gan, W.; Dai, J. A.; Jiao, M.; Xie, H.; Yao, Y.; Xiao, S.; Hu, L. A Strong, Tough, and Scalable Structural Material from Fast-Growing Bamboo. *Adv. Mater.* **2020**, *32*, No. e1906308.

(17) Luan, Y.; Yang, Y.; Chen, L.; Ma, Y.; Jiang, M.; Fei, B.; Liu, H.; Ma, X.; Zhang, X.; Sun, F.; Fang, C. Effects of Integrated Process of Flattening and Densification on the Gradient Structure and Properties of Moso Bamboo. *Constr. Build. Mater.* **2023**, *392*, 132073.

(18) Lou, Z.; Wang, Q.; Sun, W.; Zhao, Y.; Wang, X.; Liu, X.; Li, Y. Bamboo Flattening Technique: A Literature and Patent Review. *Eur. J. Wood Wood Prod.* **2021**, *79* (5), 1035−1048.

(19) Kadivar, M.; Gauss, C.; Mármol, G.; de Sá, A. D.; Fioroni, C.; Ghavami, K.; Savastano, H. The Influence of the Initial Moisture Content on Densification Process of D. Asper Bamboo: Physical-Chemical and Bending Characterization. *Constr. Build. Mater.* **2019**, *229*, 116896.
(20) Luan, Y.; Liu, L.; Ma, Y.; Yang, Y.; Jiang, M.; Semple, K.; Dai, C.; Fei, B.; Fang, C. An Integrated Hydrothermal Process of Bamboo Flattening, Densification and Drying: Mechanical Properties and Strengthening Mechanisms. *Mater. Des.* **2023**, *226*, 111610.
(21) Wang, X.; Su, N.; Chen, X.; Fei, B.; Ma, X.; Liu, H.; Miao, H.; Fang, C. Impact of Temperature on Mechanical Properties and Dimensional Stability in a Novel Gradient Pressure Bamboo Flattening Technique. *Constr. Build. Mater.* **2024**, *427*, 136258.
(22) Wang, X.; Chen, X.; Shang, L.; Chen, L.; Huang, B.; Ma, X.; Fei, B.; Liu, H.; Fang, C. A Straightforward and Efficient Gradient Pressure Method for Bamboo Flattening: Strain and Multi-Scale Deformation. *Composites, Part B* **2024**, *272*, 111232.
(23) Zhan, T.; Sun, F.; Lyu, C.; He, Q.; Xu, K.; Zhang, Y.; Cai, L.; Huang, Z.; Lyu, J. Moisture Diffusion Properties of Graded Hierarchical Structure of Bamboo: Longitudinal and Radial Variations. *Constr. Build. Mater.* **2020**, *259*, 119641.
(24) Cheng, A.; Chen, F.; Xu, K.; Xiang, J.; Wang, X.; Hu, C.; Zhou, Q.; Tu, D. Moisture Migration Mechanism of Round Bamboo in the Radial Direction during Drying. *Constr. Build. Mater.* **2024**, *435*, 136819.
(25) Chen, Q.; Fang, C.; Wang, G.; Ma, X.; Luo, J.; Chen, M.; Dai, C.; Fei, B. Water Vapor Sorption Behavior of Bamboo Pertaining to Its Hierarchical Structure. *Sci. Rep.* **2021**, *11* (1), 12714.
(26) Chen, G.; Luo, H. Effects of Moisture Content and Fibrous Structure on the Uniaxial Compression Behavior of Natural Bamboo. *Constr. Build. Mater.* **2023**, *408*, 133711.
(27) Li, H.; Jiang, M. Determination of Guaicol in Bamboo Juice from Different Kinds of Bambo with HPLC. *J. Hunan Univ. Chin. Med.* **2010**, *30*, 38−40.
(28) Liu, P.; Li, J.; Xie, H.; Teng, J.; Xu, L.; Liu, D. Main Chemical Constituents of Different Succus Bambusae. *Cent. South Pharm.* **2014**, *12*, 592−595.
(29) Hong, L.; Dangsheng, L.; Xiaohuang, J.; Mengliang, J. Preferential Study of Succus Bambusae Water Extraction Method. *J. Chin. Med. Mater.* **2009**, *32*, 620−622.
(30) Lakshmi Narasimha Rao, K.; Krishnaiah, Ch.; Babu, K. S.; Reddy, K. P. Development and Validation of a Stability-Indicating LC Method for Simultaneous Determination of Related Compounds of Guaifenesin, Terbutaline Sulfate and Ambroxol HCl in Cough Syrup Formulation. *J. Saudi Chem. Soc.* **2014**, *18*, 593−600.
(31) Boltia, S. A.; Soudi, A. T.; Elzanfaly, E. S.; Zaazaa, H. E. Simultaneous Quantification of Chlorpheniramine, Phenylephrine, Guaifenesin in Presence of Preservatives with Detection of Related Substance Guaiacol in Their Cough Syrup by RP-HPLC and TLC-Densitometric Methods. *J. Chromatogr. Sci.* **2019**, *57*, 552−559.
(32) Abdel-Naeem, H. H. S.; Sallam, K. I.; Malak, N. M. Improvement of the Microbial Quality, Antioxidant Activity, Phenolic and Flavonoid Contents, and Shelf Life of Smoked Herring (Clupea Harengus) during Frozen Storage by Using Chitosan Edible Coating. *Food Control* **2021**, *130*, 108317.
(33) Ghidoli, M.; Colombo, F.; Sangiorgio, S.; Landoni, M.; Giupponi, L.; Nielsen, E.; Pilu, R. Food Containing Bioactive Flavonoids and Other Phenolic or Sulfur Phytochemicals With Antiviral Effect: Can We Design a Promising Diet Against COVID-19? *Front. Nutr.* **2021**, *8*, 661331.
(34) Hodaei, M.; Rahimmalek, M.; Arzani, A.; Talebi, M. The Effect of Water Stress on Phytochemical Accumulation, Bioactive Compounds and Expression of Key Genes Involved in Flavonoid Biosynthesis in Chrysanthemum Morifolium L. *Ind. Crops Prod.* **2018**, *120*, 295−304.
(35) Shi, L.; Zhao, W.; Yang, Z.; Subbiah, V.; Suleria, H. A. R. Extraction and Characterization of Phenolic Compounds and Their Potential Antioxidant Activities. *Environ. Sci. Pollut. Res. Int.* **2022**, *29* (54), 81112−81129.
(36) M'hiri, N.; Ioannou, I.; Mihoubi Boudhrioua, N.; Ghoul, M. Effect of Different Operating Conditions on the Extraction of Phenolic Compounds in Orange Peel. *Food Bioprod. Process.* **2015**, *96*, 161−170.
(37) Sato, T.; Ikeya, Y.; Adachi, S.; Yagasaki, K.; Nihei, K.; Itoh, N. Extraction of Strawberry Leaves with Supercritical Carbon Dioxide and Entrainers: Antioxidant Capacity, Total Phenolic Content, and Inhibitory Effect on Uric Acid Production of the Extract. *Food Bioprod. Process.* **2019**, *117*, 160−169.
(38) Zhichao, L.; Chenglong, Y.; Yanjun, L.; Shen, D.; Yang, L.; Liu, J.; Zhang, A. Effect of Saturated Steam Treatment on the Chemical Composition and Crystallinity of Bamboo Bundles. *J. For. Eng.* **2020**, *5*, 29−35.
(39) Li, X.; Liu, Y.; Gao, J.; Wu, Y.; Yi, S.; Wu, Z. Characteristics of FTIR and XRD for Wood with High-Temperature Heating Treatment. *J. Beijing For. Univ.* **2009**, *31* (S1), 104−107.
(40) Wang, M.; Harries, K. A.; Zhao, Y.; Xu, Q.; Wang, Z.; Leng, Y. Variation of Mechanical Properties of P. Edulis (Moso) Bamboo with Moisture Content. *Constr. Build. Mater.* **2022**, *324*, 126629.
(41) Liu, Y.; Li, H.; Dauletbek, A. Effects of Natural Weathering on the Mechanical Properties of Moso Bamboo Internodes and Nodes. *Constr. Build. Mater.* **2024**, *417*, 135313.
(42) Runhe, S.; Xianjun, L.; Yuan, L.; Hou, R. Effect of High Temperature Heat Treatment on FTIR and XRD Characteristics of Bamboo Bundles. *J. Cent. South Univ. For. Technol.* **2013**, *33*, 97−100.
(43) Kadivar, M.; Gauss, C.; Mármol, G.; de Sá, A. D.; Fioroni, C.; Ghavami, K.; Savastano, H. The Influence of the Initial Moisture Content on Densification Process of D. Asper Bamboo: Physical-Chemical and Bending Characterization. *Constr. Build. Mater.* **2019**, *229*, 116896.
(44) Yuan, T.; Wang, Z.; Han, X.; Yuan, Zh.; Wang, X.; Li, Y. Multi-Scale Evaluation of the Effect of Saturated Steam on the Micro-mechanical Properties of Moso Bamboo. *Holzforschung* **2021**, *75*, 1052−1060.
(45) Wang, X.; Su, N.; Chen, X.; Fei, B.; Ma, X.; Liu, H.; Miao, H.; Fang, C. Impact of Temperature on Mechanical Properties and Dimensional Stability in a Novel Gradient Pressure Bamboo Flattening Technique. *Constr. Build. Mater.* **2024**, *427*, 136258.

https://doi.org/10.1021/acsomega.4c11224
ACS Omega 2025, 10, 7362−7370