

Enhancing Dyeing Efficiency of Bamboo Culm through Surface Sanding: Modifying Microstructure and Permeability for Improved Dyeing Performance

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15

16 **Abstract**

17 Bamboo products are increasingly popular among consumers; however, their
18 monotonous surface coloration and inherent natural defects limit their economic
19 value. To address them, this study investigated the dyeing performance of bamboo
20 culms after surface sanding treatment. The individual and interactive effects of
21 sanding removal amount, microstructural changes, dye penetration depth and dyeing

duration on dyeing performance were evaluated. The results showed that sanding treatment reduced the surface silicon content of bamboo by 22.9% and increased its surface roughness by 16.81%. As the sandpaper grit size increased, the surface roughness decreased, cell structural damage was reduced, and pits on the cell walls remained observable on the bamboo culm surface. After dyeing, the bamboo culms showed distinct color differences compared with undyed bamboo. Both prolonging the dyeing time and increasing the sanding removal amount enhanced dye penetration depth and had darkened the surface color. Sanding improved the surface wettability of bamboo, promoted more uniform surface dyeing and improved dyeing efficiency, but reduced surface gloss. Following Jurin's law, the dye adsorption rate was significantly enhanced. The dye adhered via physical adsorption without new chemical bonds. Light fastness tests showed that dyed bamboo faded after 124 h of xenon lamp irradiation. Among the tested samples, unsanded bamboo dyed for 4 h, sanded bamboo dyed for 30 min and bamboo with a sanding removal amount of 3-4 g showed better light fastness, with grades of 3-4, 3-4 and 3, respectively. This research provides a new strategy for bamboo dyeing in eco-friendly construction and decoration.

Keywords: bamboo; dyeing; lightfastness; sanding treatment; surface roughness

1 Introduction

Bamboo is one of the world's most important renewable biomass resources (Chen et al. 2021). Owing to its short growth cycle, widespread distribution, and high economic value (Binfield et al. 2025), bamboo has been utilized in various fields, including tableware (Chen et al., 2023), papermaking (Netto et al. 2024), and building materials (Lian et al. 2024). In China, Moso bamboo (*Phyllostachys edulis*) accounts for the largest proportion of both bamboo forest area and standing stock. However, the natural surface color of bamboo is relatively monotonous, and traditional bamboo products commonly exhibit a pale yellow appearance. Furthermore, bamboo is prone to developing surface defects during natural growth, harvesting, and transportation. These defects not only compromise appearance uniformity but also reduce the commercial value of bamboo products. To enhance the decorative properties of bamboo, meet diverse consumer demands, and mitigate the negative effects of surface defects, surface dyeing has been recognized as an effective approach.

Moso bamboo is primarily composed of parenchyma cells, fibers, and vascular tissues, including vessels, sieve tubes, and companion cells (Li et al. 2025). These tissues are arranged regularly in the longitudinal direction within the internodes. Unlike wood, bamboo internodes lack transversely arranged ray cells, resulting in significantly lower transverse permeability compared than longitudinal permeability. Furthermore, the bamboo surface is covered by a wax layer, composed of hydrocarbons, fatty acids and a siliceous layer, primarily existing as SiO₂ (Zhu et al. 2024). Although these layers protect bamboo in its natural environment, they act as

barriers during transverse penetrating. Therefore, surface pretreatment is essential for improving bamboo permeability.

Previous studies on bamboo dyeing have shown that ultrasonic treatment can shorten the required dyeing time while enhancing color fastness and color uniformity (Chung et al. 2014). The addition of glacial acetic acid or tannic acid during dyeing can further improve color fastness (Chung et al. 2017). Although drying pretreatment can evenly redistribute surface wax and improve the dyeing effect and gloss, it results in poor light-aging resistance (Cheng et al. 2024). Moreover, synergistic treatment with plant dyes and metal mordants can modify bamboo color and enhance mildew resistance (Li et al. 2025). However, relatively few studies have focused on the dyeing of bamboo culms or the effect of surface structure on their dyeing performance.

Sanding is a simple and efficient surface treatment method, widely used in wood processing to achieve the desired surface quality and dimensional accuracy (Zhang et al. 2023). Higher sandpaper grit sizes correspond to smaller abrasive particles, and thus lower surface roughness. Coarse sanding removes major surface irregularities and excess material, whereas fine sanding provides final smoothing and prepares the surface for subsequent treatments (Adamcik et al. 2024). Sanding bamboo surfaces produces cracks, micropores, and sanding marks and reduces surface wax and silicon contents (Chen et al. 2022). Treating with sandpapers of different grit sizes produces bamboo surfaces with varying roughness; however, surface wettability does not necessarily increase with increasing roughness (Zhang et al. 2024). Sanding

pretreatment enhances the adhesion of subsequent coatings to bamboo surfaces (Choi et al. 2025).

This study focuses on sanding treatment of the bamboo green layer. To investigate the effects of process parameters, including sanding treatment, dyeing time, and sanding removal amount, on the surface dyeing performance of bamboo culms, three independent experiments were conducted. The bamboo culms were cut into smaller specimens, and then dyed under predefined conditions. The surface dyeing performance of both sanded and unsanded bamboo culms was investigated, and the effects of these parameters on gloss, color, dye penetration depth, and color fastness were examined. The findings reveal the synergistic effect of sanding and dyeing treatment on bamboo culms and provide practical guidance and technical support for the high-value utilization of bamboo.

2 Materials and methods

2.1 Materials

The four-year-old Moso bamboo (*Phyllostachys edulis*) was harvested from Anji County, Zhejiang Province. The Bamboo culms were obtained at a height exceeding 1.5 m from the root with a length of approximately 4 m. Culms were cut with a height of 50 mm (± 3 mm). Intact bamboo culms without node with a diameter of 60 mm (± 5 mm) were selected as the experimental samples, to keep the size of each bamboo sample consistent, so the sanding removal per unit area are same. The surface dust and dirt of bamboo culms were wiped off and then placed in a cool place for natural

air-drying. Mixing ratio of the dyes was 30:60:20 (Acid Yellow159: Acid Red 336: Acid Blue264) corresponding to an actual dosage of 30 g, 60 g and 20 g for each dye, respectively. These three dyes are the main dyes used in the industrial production of wood and bamboo materials.

2.2 Methods

2.2.1 Pretreatment of bamboo surface

To systematically investigate the effects of process parameters (sanding treatment, dyeing time, and sanding removal amount) on the surface dyeing performance of bamboo culms, three independent experiments were designed. To ensure consistent material removal per unit area during sanding, all culms measuring 50 mm (± 3 mm) in height and 60 mm (± 5 mm) in diameter were selected as the experimental specimens and all sanding operations were performed manually. Dyeing time was set at three levels (2 h, 4 h, and 6 h) to analyze the effect of dyeing time on the surface color of untreated bamboo culms. In order to investigate the effect of dyeing time on the surface color of sanded bamboo culms, the bamboo green was sanded along the longitudinal direction using 180-grit sandpaper with a sanding removal amount of 4 g (± 0.2 g), and the dyeing time was set at three levels (10 min, 30 min, and 2 h). In order to investigate the effect of sanding removal amount on the surface color of bamboo culms, the bamboo green was sanded along the longitudinal direction, starting with 180-grit sandpaper, then 400-grit, and finishing with 800-grit sandpaper. Sanding removal amount was set at three levels (1–2 g, 3–4 g, and 6–7 g), and the

dyeing time was set at 30 min. Five samples were tested for each level of the experiments.

2.2.2 Dyeing of bamboo surface

The pretreated and untreated bamboo culms were immersed into the prepared dye solution at temperature of 95°C. Mixing ratio of the dyes was 30:60:20 (Acid Yellow159: Acid Red 336: Acid Blue264) corresponding to an actual dosage of 30 g, 60 g and 20 g for each dye, respectively. The solid dyes were fully dissolved in 30 kg of water to prepare the dye bath, with a final dye mass fraction of 0.37%. Glacial acetic acid was added to the dye bath as a penetrant. After dyeing for the preset duration, the bamboo culm samples were retrieved from the dye bath, drained of excess dye solution, and dried of the samples. The samples were prepared as presented in Fig. 1.

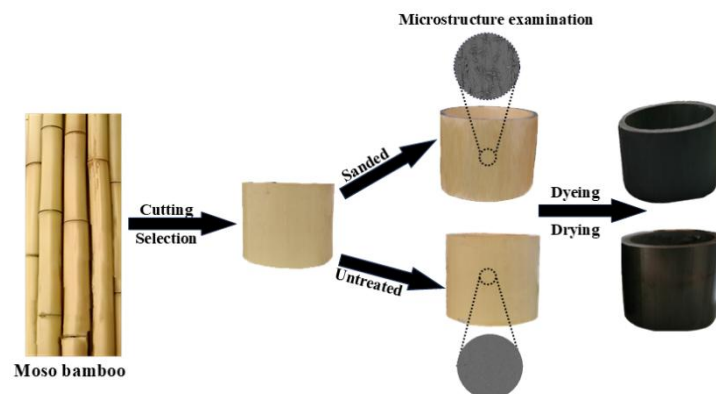


Fig. 1 Dyeing preparation process of unsanded and sanded bamboo culms

2.2.3 Microstructure changes

The sliding microtome (REM-710, Yamato, Japan) was used to prepare 4 bamboo culm samples with dimensions of 5 mm × 5 mm × 4 mm (longitudinal direction × tangential direction × radial direction), including unsanded bamboo culm, and three sets of bamboo culms sanded with 180-grit, 400-grit, and 800-grit sandpapers. Scanning electron microscope (SEM; Phenom XL, Thermo Fisher Scientific, USA) was used to observe the microstructure changes. Also, energy dispersive spectrometer (EDS) was employed to analyze the elemental on the sample surfaces, respectively.

2.2.4 Glossiness and color changes

Surface glossiness of the bamboo culm samples was tested using a glossmeter (MG6-F1, KSJ Photoelectrical Instruments Co., Ltd., China) with an incident angle of 60°. For each group, 4 replicate test points were collected on the surface of each of the 5 parallel samples. The average value was taken as the test result. The color parameters of the samples were measured before and after dyeing, and characterized according to CIE L*, a* and b* standard chromaticity system by the International Commission on Illumination (Cheng et al. 2023). The chromaticity index of the bamboo culms from the 3 experimental groups were measured with a chroma meter (NR10QC, 3NH Technology Co., Ltd., China). For each group, 2 replicate test points were selected on the surface of each of the 5 parallel samples, and the average value was taken as the test result. The color difference formula is expressed as the following equations:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

$$\Delta L^* = L^* - L_0^* \quad (2)$$

$$\Delta a^* = a^* - a_0^* \quad (3)$$

$$\Delta b^* = b^* - b_0^* \quad (4)$$

Where ΔE^* represents the total color difference of the samples. L^* , a^* and b^* are the luminosity, red-green factor, and yellow-blue factor of the samples before dyeing. L_0^* , a_0^* and b_0^* are the luminosity, red-green factor, and yellow-blue factor of the samples after dyeing.

2.2.5 Surface roughness

The surface roughness of bamboo culm samples with different surface treatments (untreated, sanded with 180-grit sandpaper, and sanded with 800-grit sandpaper) was characterized using an automatic zoom 3D surface profilometer (InfiniteFocus G5, Alicona Corporation, Austria). The samples were prepared to a dimension of approximately 5 mm × 5 mm × 1 mm (length × width × thickness), and the magnification of the profilometer was set as 10.

2.2.6 X-Ray Photoelectron Spectroscopy (XPS)

The surface chemical composition of untreated, 180-grit sanded, and 180-grit sanded and dyed bamboo samples was measured using X-ray Photoelectron Spectroscopy (XPS; AXIS UltraDLD, Shimadzu, Japan). The samples (dimension: 4 mm × 4 mm × 1 mm, length × width × thickness) were scanned in an analysis chamber with a vacuum degree of 7×10^{-8} Pa, using a monochromatic Al K α X-ray source (1486.6 eV) at a scanning power of 600 W and a step size of 0.1 eV.

2.2.7 Attenuated Total Refraction-Fourier Transform Infrared Spectroscopy

(ATR-FTIR)

Surface chemical functional group changes of unsanded, 180-grit sanded, and 180-grit sanded and dyed bamboo culm were characterized via Attenuated Total Reflection Fourier Transform Infrared Spectroscopy (ATR-FTIR; VERTEX 80V, Bruker, Germany), with a resolution of 4 cm^{-1} and a wavelength range of 400 to 4000 cm^{-1} .

2.2.8 Contact angle

Static water contact angle (WCA) measurements were carried out on four groups of samples, which are unsanded bamboo, unsanded dyed bamboo, 180-grit sanded bamboo, and 180-grit sanded dyed bamboo, using a contact angle tester (FCA2000A2, Shanghai AFES Precision Instrument Co., Ltd., China). For each sample group, 6 random replicate measurements were conducted. During each measurement, deionized water with a volume of $10\text{ }\mu\text{L}$ was used as the probe liquid, and the ambient temperature was kept constant at $20\text{ }^{\circ}\text{C}$. Image was acquired after the morphology of the water droplet stabilized for 30 s. The mean value of the measurements for each group was adopted as the final WCA result.

2.2.9 Dye penetration depth

Each group of dyed bamboo culm samples was longitudinally split to expose the radial section. Then the radial surface of the samples was polished with a sliding microtome. Subsequently, the dye penetration depth of the samples was observed and imaged using a stereomicroscope (SZ2-ILST, Olympus Corporation, Japan). Finally,

scale calibration of all acquired micrographs was performed using Image J software (National Institutes of Health, USA) before dimensional measurement. For each sample, the dye penetration depth was measured at 20 evenly distributed measurement points and the average value was taken as the test result.

2.2.10 Light fastness

The light fastness of dyed bamboo culm samples was conducted via a xenon lamp aging test chamber (BR-4000, Beier, China). A total of 3 experimental groups were set, and 6 replicate test points were collected on the surface of each of the 2 parallel samples. The samples and blue wool standards were exposed together under a xenon arc lamp. The color parameters of the samples were tested when samples were irradiated for 0, 28, 52, 76, 100, and 124 h. The total color difference (ΔE^*) between unexposed and exposed samples was calculated according to Equation 1, based on the CIELAB color space. The degree of discoloration of the samples was evaluated in accordance with GB/T 250-2008 (Textiles - Tests for color fastness - Grey scale for assessing change in color) and the light fastness grade of the dyed bamboo culms was determined accordingly.

3 Results and discussion

3.1 Microstructure changes

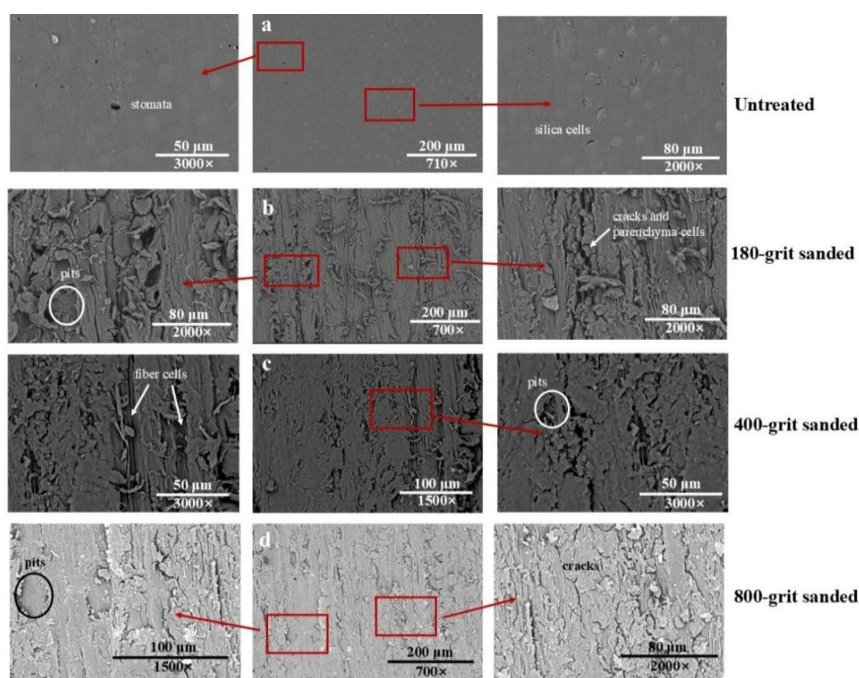


Fig. 2 SEM images of (a) unsanded, (b) 180-grit sanded, (c) 400-grit sanded and (d) 800-grit sanded green surface of bamboo culms

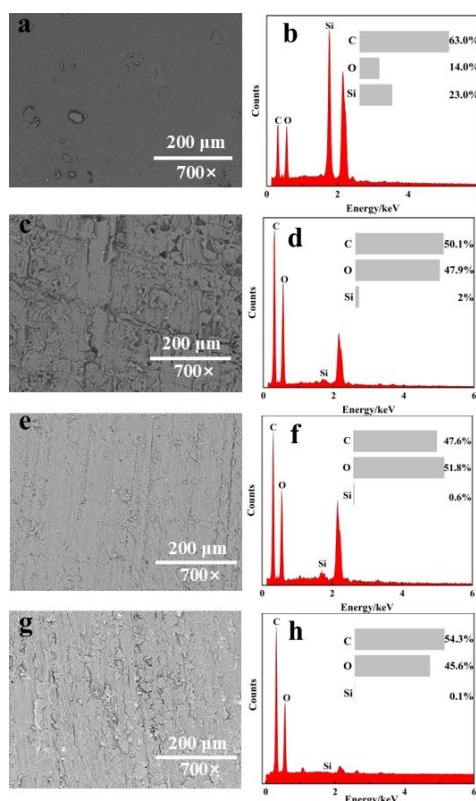


Fig. 3 Elements distribution of (a) untreated, (c) 180-grit sanded, (e) 400-grit sanded (g) 800-grit sanded green surface of bamboo culms, and corresponding spectrum of

element distribution of (b) untreated, (d) 180-grit sanded, (f) 400-grit sanded and (h) 800-grit sanded

SEM images and EDS spectra reveal the morphological and elemental differences in bamboo culms before and after sanding treatment (Fig. 2 and 3). The mass of bamboo culm removed by 180-grit sanding was 4 g. Following 180-grit sanding, sanding with 400- and 800-grit papers removed an additional 1 g each. The surface of the untreated bamboo culm (Fig. 2a) appeared relatively flat, displaying numerous white circular spots (silica cells) and few stomata. Stomata regulate cuticular transpiration and facilitate the entry of chemicals into the epidermis (Enyinwa et al. 2023). Compared with the unsanded surface, the 180-grit sanded sample (Fig. 2b) exhibited severe structural damage and increased roughness, with abundant broken protrusions, unexfoliated cell structures, and exposed parenchyma cells and fiber cells including their cell lumens. Pits were also observed on the cell walls. In contrast, the 400-grit sanded sample (Fig. 2c) was relatively flat but remained rougher than the untreated sample. It showed distinct parallel longitudinal sanding marks, pits on the cell walls and limited damage to the cell structures. The 800-grit sanded sample (Fig. 2d) was flatter than the 400-grit sanded sample, but still showed cracks and pits on the cell wall. EDS analysis revealed a high silicon (Si) content on the unsanded bamboo surface, which decreased sharply after sanding treatment (only 0.1% remaining Si on the 800-grit treated surface). This reduction can be attributed to progressive sanding

of the siliceous layer with successive sanding (180, 400, and 800-grit). The cumulative material removal increased progressively across successive sanding stages, ultimately resulting in the near-complete elimination of silicon (Si) from the sanded bamboo surface (He et al. 2022). Microstructural analysis showed that sanding treatment increased the surface roughness of bamboo and exposed inner cell structures and pits on the cell walls. These changes can expose more hydroxyl groups, and increase the contact area between the bamboo surface and the dye liquor, thereby enhancing dye penetration into the bamboo. Additionally, the marked reduction in Si content in the bamboo green layer after sanding, together with the increased surface roughness, improved the wettability and permeability of bamboo culms.

3.2 Glossiness and color changes

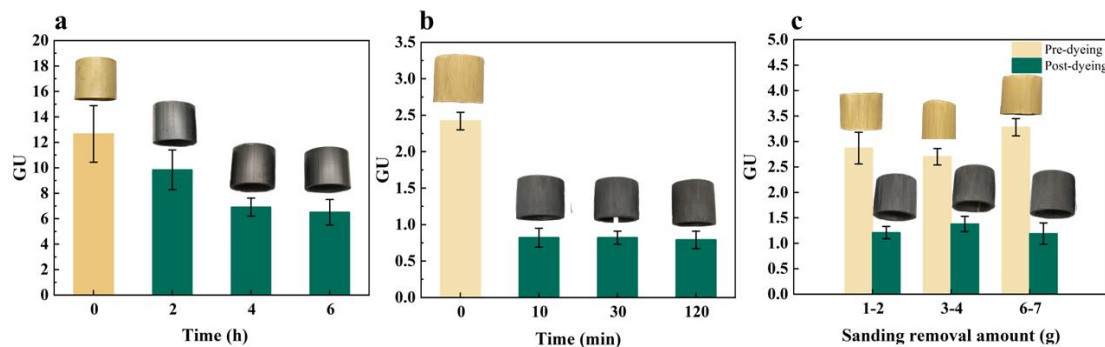


Fig. 4 Gloss of dyed bamboo: (a–c) untreated samples with dyeing duration of 2 h, 4 h, and 6 h, respectively; (d–f) samples sanded with 180-grit with dyeing duration of 10 min, 30 min, and 120 min, respectively; (g–i) dyed samples with sanding removal amount of 1–2 g, 3–4 g, and 6–7 g, respectively

Table. 1 Parameters for changes in surface color and gloss of dyed bamboo as affected by no treatment, 180-grit sanding treatment and sanding removal amount

Time/h	L*	a*	b*	ΔE^*
0	68.47(2.18)	3.89(1.54)	26.09(1.48)	
2	33.19(1.46)	-1.28(0.30)	-0.43(0.03)	44.44(1.69)
4	31.86(4.24)	-0.51(0.10)	-0.13(0.08)	45.25(2.18)
6	31.52(1.29)	-0.41(0.04)	-0.24(0.03)	45.57(1.67)
Time/min	L*	a*	b*	ΔE^*
0	63.19(2.49)	5.74(0.72)	30.08(2.34)	
10	29.26(0.22)	-1.34(0.01)	-0.64(0.24)	46.31(1.61)
30	27.93(0.47)	-0.98(0.12)	-0.66(0.36)	47.25(1.68)
120	25.94(0.73)	-0.61(0.01)	-0.48(0.05)	50.52(1.62)

Sanding amount /g	Treatment process	L*	a*	b*	ΔE^*
1-2	Before dyeing	63.1(0.79)	7.44(0.25)	31.77(1.26)	
	After dyeing	28.69(2.21)	-0.95(0.04)	-0.98(0.08)	48.24(1.47)
3-4	Before dyeing	65.00(3.18)	7.83(1.17)	28.87(3.02)	
	After dyeing	28.56(0.63)	-0.82(0.01)	-1.12(0.02)	47.98(1.85)
6-7	Before dyeing	64.47(1.86)	7.80(0.72)	29.45(1.40)	
	After dyeing	27.06(0.19)	-0.90(0.02)	-0.82(0.03)	48.90(1.33)

274

275 Fig. 4 and Table 1 summarize the changes in surface gloss and color and changes of
276 dyed bamboo culm samples subjected to different sanding treatment (unsanded, 180-
277 grit sanded, and different sanding removal amounts). Compared with the
278 corresponding undyed culms, all dyed groups exhibited significant changes in ΔL^* ,
279 Δa^* , Δb^* , and ΔE^* . The negative ΔL^* , Δa^* , and Δb^* values indicate that the dyed
280 bamboo culms became darker, with colors shifting toward green and blue, showing a
281 significant color difference from the untreated bamboo culms (Zhu et al. 2024). For
282 the unsanded and 180-grit sanded groups, ΔL^* continuously decreased with prolonged
283 dyeing time, whereas Δa^* and ΔE^* gradually increased, indicating that as dyeing time
284 increased, the bamboo culms became darker and slightly redder, and the color
285 difference between the dyed and undyed culms increased. The Δb^* value of the
286 unsanded sample initially increased and then decreased. In contrast, the Δb^* value of

the 180-grit sanded samples initially decreased and then increased. Visual observation revealed slight color unevenness on the surfaces of unsanded bamboo dyed for 2 h and sanded bamboo dyed for 10 min. This may be attributed to the insufficient dyeing time, which prevented the dye from fully adhering to the surface. As dyeing time increased, more dye solution penetrated the bamboo surface, resulting in a more uniform surface color but lower luminosity. The 180-grit sanding treatment removed most of the waxy and siliceous layers from bamboo surface, and the rougher surface and exposed cell structures facilitated dye adhesion. This enabled a distinct dyeing effect in a shorter time and significantly improved dyeing efficiency compared with the unsanded group. With an increased sanding removal amount, ΔL^* and Δa^* decreased, corresponding to a darker and greener surface. In contrast, Δb^* initially increased and then decreased, while ΔE^* initially decreased and then increased, with no significant fluctuation. Overall, the unsanded samples showed a clear color difference after dyeing, with minor variation across different dyeing durations, and exhibited higher surface gloss than sanded samples both before and after dyeing because of the intrinsic negative correlation between gloss and surface roughness. The gloss of all samples further decreased with prolonged dyeing time. This is because the rough surface of sanded bamboo causes light to scatter repeatedly on the surface, forming diffuse reflection and reducing glossiness (Chen et al. 2025).

3.3 Surface roughness

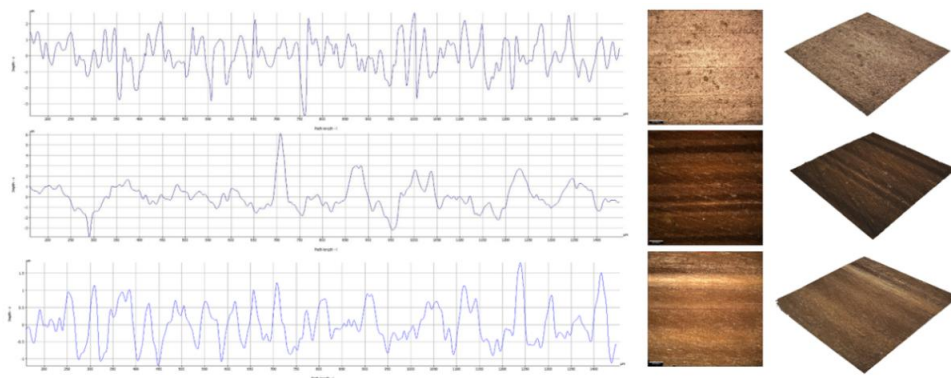


Fig. 5 Surface roughness of untreated ,180-grit treated and 800-grit treated bamboo culms

Table. 2 surface roughness parameters of untreated ,180-grit treated and 800-grit treated bamboo culms

	$Ra/\mu m$	$Rq/\mu m$	$Rt/\mu m$	Rsk	$Rsm/\mu m$	Rku
Untreated bamboo	0.833	1.058	6.610	-0.198	55.5	3.352
180-grit treated bamboo	0.973	1.301	10.003	0.791	169.376	5.452
800-grit treated bamboo	0.460	0.564	3.003	0.376	73.235	2.730

Fig. 5 shows the surface profile curves and two-dimensional and three-dimensional surface profiles of unsanded bamboo culms, 180-grit sanded bamboo culms, and 800-grit sanded bamboo culms, respectively. Both the 180-grit and 800-grit treatments

317 were performed with the same total sanding removal amount of 4 g. The
318 corresponding roughness parameters are listed in Table 2. The surface profile of the
319 180-grit sanded sample ranged from $-4\text{ }\mu\text{m}$ to $6.5\text{ }\mu\text{m}$, which was much larger than
320 those of the unsanded sample ($-3.5\text{ }\mu\text{m}$ to $3\text{ }\mu\text{m}$) and the 800-grit sanded sample (-1.5
321 μm to $2\text{ }\mu\text{m}$). R_a , R_q , and R_t represent the arithmetic mean roughness, root mean
322 square roughness, and maximum peak-to-valley height of the sample profile,
323 respectively. These parameters of the tested samples showed an initial increasing and
324 then decreasing trend with increasing sandpaper grit size, with the lowest values
325 detected in the 800-grit sanded group. This is because, during sanding with 180-grit
326 sandpaper, its large abrasive grains can significantly damage the originally smooth
327 and flat bamboo culm surface, forming new peaks and valleys. In contrast, 800-grit
328 sandpaper has smaller abrasive grains, resulting in less damage to the bamboo culm
329 surface and a smaller vertical distance between the highest peak and the lowest valley,
330 thereby producing a smoother, more uniform, and more regular surface. This was
331 consistent with the 3D surface observations and SEM results of the sanded bamboo
332 samples. R_{sk} , R_{ku} , and R_{sm} represent the skewness, kurtosis, and mean width of the
333 sample profile, respectively. Comparative analysis showed that the 180-grit sanded
334 sample had more high peaks, fewer deep valleys, more distinct peak-valley features,
335 larger peak-valley spacing, and a relatively sparse surface texture, thereby disrupting
336 the fine, dense texture of the pristine unsanded surface. The 800-grit sanded surface

retained rounded and smooth peaks and a denser texture (Zhang et al. 2025), which is consistent with the SEM observations.

3.4 Changes of chemical constituents

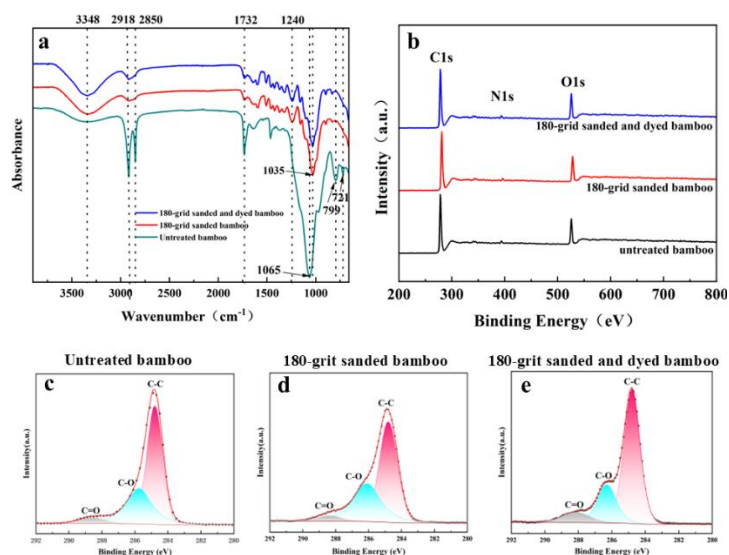


Fig. 6 Infrared spectrogram of untreated bamboo, 180-grit sanded bamboo and 180-grit sanded and dyed bamboo (a). XPS full spectra (b), C1s spectra of untreated bamboo (c), 180-grit sanded bamboo (d) and 180-grit sanded and dyed bamboo (e)

Table. 3 Distribution of O and C1, C2, C3 of untreated bamboo, sanded bamboo and dyed bamboo

Samples	O%	C%	O/C	C1%	C2%	C3%
Untreated bamboo	13.77	83.85	0.16	61.74	33.60	4.66
Sanded bamboo	17.51	79.87	0.22	57.93	38.13	3.94
Dyed bamboo	17.65	80.20	0.22	67.76	23.33	8.91

Fig. 6a shows the ATR-FTIR spectra of unsanded, 180-grit-sanded, and 180-grit-sanded and dyed bamboo culms. Sanding increased the band at 3348 cm^{-1} , assigned to -OH stretching in cellulose, hemicellulose, and lignin, indicating greater surface exposure of hydroxyl groups. In contrast, the C-H stretching bands at 2918 and 2850 cm^{-1} weakened, and the peaks at 721 and 1732 cm^{-1} disappeared, suggesting removal of aliphatic components from the bamboo wax layer (Che et al. 2025). The disappearance of the Si-O band at 799 cm^{-1} and the weakened Si-O-Si band at 1065 cm^{-1} further indicate damage to the siliceous layer (Wang et al. 2015). New peaks at 1240 and 1035 cm^{-1} , were attributed to C-O and C-O-C vibrations in hemicellulose and cellulose (Xu et al. 2025). No new characteristic peaks appeared in the dyed sample, indicating that no new functional groups were formed and that the dye was mainly adsorbed on the bamboo surface. However, the dyed bamboo showed stronger bands at 3348 and 2918 cm^{-1} , likely due to the -OH and C-H groups in the dye.

XPS analysis (Fig. 6 b-e and Table 3) showed N1s peaks in all samples, which can be attributed to trace protein in bamboo and N-containing bonds in the dye. The C1s envelope was deconvoluted into C1 (C-H/C-C), C2 (C-O), and C3 (C=O/O-C-O); C1 is associated with lignin, whereas C2 and C3 reflect cellulose and hemicellulose (Xia et al. 2024). Sanding increased the O/C ratio, indicating exposure of more carbohydrates (Liu et al. 2022). After dyeing, both O and C contents increased because the dye covered the bamboo surface. The C1/C2 ratio decreased after sanding, suggesting greater exposure of hydrophilic cellulose and hemicellulose

(Meng et al. 2024). After dyeing, C1 and C3 increased from 57.93% to 67.76% and from 3.94% to 8.91%, respectively, whereas C2 decreased due to the increased proportions of C1 and C3.

3.6 Contact angle analysis

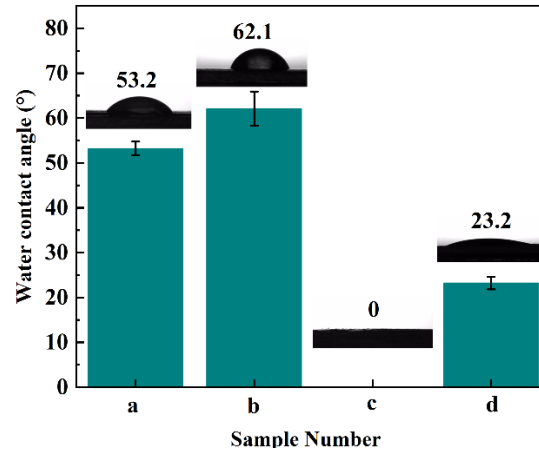


Fig. 7 Static water contact angles of bamboo samples: (a) unsanded bamboo, (b) unsanded dyed bamboo, (c) 180-grit sanded bamboo, and (d) 180-grit sanded dyed bamboo

As shown in Fig. 7, the contact angles of unsanded, unsanded and dyed, 180-grit-sanded, and 180-grit-sanded and dyed bamboo culms are presented, respectively. The waxy and siliceous layers on the surface of unsanded bamboo hinder the effective wetting and spreading of water (Fig. 7a). After dyeing, no significant change in the water contact angle was observed, with only a marginal increment of 8.9° (Fig. 7b). The 180-grit sanding treatment could remove the waxy and siliceous layers from the bamboo surface, enhancing wetting and water adsorption on the surface (Fig. 7c) (Chen et al. 2022). Meanwhile, the surface roughness induced by 180-grit sanding

further enhanced the intrinsic hydrophilicity of bamboo via the Wenzel effect: the roughened surface enlarges the solid-liquid contact area (Wu et al. 2022), ultimately driving the complete spreading of water droplets on the sanded bamboo substrate. In addition, greater surface roughness leads to a smaller contact angle (Chen et al. 2016). After dyeing, the water contact angle of the sanded bamboo increased from complete wetting (0°) to 23.2° (Fig. 7d), corresponding to a reduction in surface hydrophilicity. This phenomenon could be ascribed to two primary mechanisms. On the one hand, the successful immobilization of dye molecules on the bamboo surface shielded some polar hydroxyl sites. On the other hand, the inherent hydrophobic moieties of the dye molecules (e.g., aromatic rings) covered the material surface, thereby lowering the overall surface polarity, which ultimately manifested as an increase in contact angle and a reduction in hydrophilicity. The adhesion of dye molecules to the bamboo surface via physical adsorption was consistent with the conclusions obtained from ATR-FTIR characterization.

3.7 Dye penetration depth

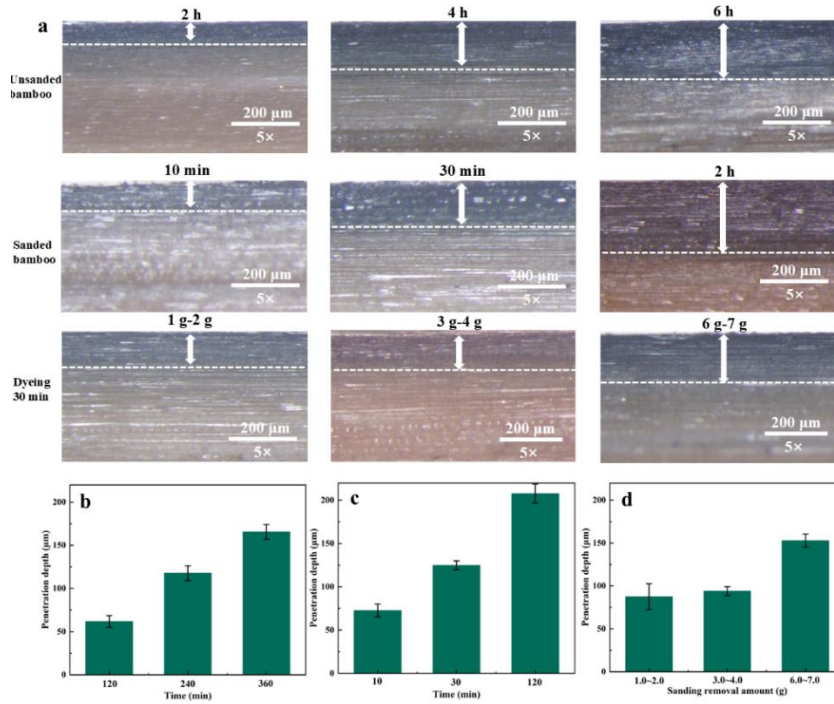


Fig. 8 (a) The stereomicroscope images of the radial sections of bamboo culms, (b) Dyeing time and dye penetration depth of unsanded bamboo, (c) Dyeing time and dye penetration depth of bamboo segments with 180-grit sanding treatment, (d) Bamboo segments with different sanding removal amounts and dye penetration depth

Fig. 8 presents stereomicroscope images of the radial cross-sections of bamboo culms from different dyeing groups. The dye penetration depth was quantitatively measured using ImageJ software. Dye penetration depth is a core indicator for evaluating the dyeing performance of bamboo. Its variation pattern is governed by two key factors, interfacial wettability and internal mass transfer channels, and can be systematically explained by classical wetting theory and capillary mass transfer theory.

For unsanded bamboo culms, the dye penetration depth (Fig. 8b) showed a gradual increase with prolonged dyeing time: at 120 min of dyeing, it reached only 61.85 μm ,

and even when extended to 360 min, the depth increased only to 165.62 μm . The fundamental reason is that the surface of unsanded bamboo is covered with an intact bamboo green layer, which is composed of a dense siliceous layer and a waxy layer (Zhu et al. 2024), with a silicon content as high as 23% and a water contact angle of 53.2°, indicating relatively strong hydrophobicity. According to the Cassie-Baxter wetting model, when a liquid contacts the hydrophobic surface of the bamboo green, it cannot completely fill the microscopic grooves on the surface; instead, it forms trapped air pockets in the grooves, leading to a substantial reduction in the actual solid–liquid contact area and thereby making it difficult for the dye solution to spread and penetrate (Li et al. 2022). Meanwhile, there are almost no connected pores or pit channels in the bamboo green layer, which further hinders the dye diffusion into the bamboo interior and constitutes the core mechanism underlying the extremely low dyeing efficiency of unsanded bamboo.

The dye penetration depth of sanded bamboo culms exhibited the same time dependence as that of the unsanded group, but its penetration rate and final depth were significantly improved: at 10 min of dyeing, it reached 72.70 μm , and at 120 min of dyeing, it further increased to 207.68 μm . The penetration rates of bamboo sanded with 180-grit at 30 min and 120 min were 7.27 $\mu\text{m}/\text{min}$ and 1.73 $\mu\text{m}/\text{min}$, respectively, both significantly higher than the 0.52 $\mu\text{m}/\text{min}$ penetration rate of the unsanded bamboo after 2 h of dyeing. This corresponds to a 232.7% increase in the dye penetration rate. This result can be explained by the Wenzel wetting model and

the capillary rise law. Sanding treatment first completely removed the hydrophobic barrier layer of the bamboo green, which contain high levels of silicon and wax, thereby converting the substrate into a hydrophilic bamboo parenchyma tissue (with a water contact angle of 0°). On this basis, the microscopic grooves and pores generated by sanding increased the surface roughness. According to the Wenzel model, for a hydrophilic surface, an increase in roughness of the bamboo surface further reduces the apparent contact angle and thus significantly improves surface wettability (Li et al. 2025). Meanwhile, the cracks, fiber lumina, parenchyma cell lumina, and pits on cell walls exposed during sanding constitute a large number of transverse mass transfer channels. This could increase the effective contact area, expose more adsorption sites, and consequently promote the wettability of the bamboo surface. In the primary functional zone of bamboo surface dyeing, the lateral penetration of the dye solution is primarily governed by Jurin's law (Su et al. 2025):

$$h=2\gamma\cos\theta/\rho gr \quad (5)$$

where h represents the capillary rise height of the samples; γ , θ , ρ , g , and r represent the surface tension, contact angle, liquid density, gravitational acceleration, and capillary radius, respectively.

The improvement in wettability increases the $\cos\theta$ value, which in turn significantly enhances the rise height and velocity of the dye solution in these capillary channels, thereby enabling deeper dye penetration within a shorter dyeing time.

The dye penetration depth of bamboo culms (Fig. 8c) showed a continuously increasing trend as the sanding removal amount increased. When the sanding removal amount was 1–2 g, the penetration effect was poor: the average depth was only 87.52 μm , and the standard deviation was relatively large. The reason was that this removal amount was insufficient to completely remove the bamboo green layer, leaving a siliceous hydrophobic barrier on the surface, thereby leading to significant wettability differences among different regions. When the sanding removal amount was increased to 6–7 g, the penetration depth of the specimens significantly increased to 152.86 μm . At this point, the bamboo green layer was completely removed, and the deeper cell structures were exposed, thereby forming more abundant mass transfer channels. It is worth noting that the average penetration depth of the specimen with a sanding removal amount of 3–4 g was smaller than that of the specimen sanded with 180 mesh sandpaper and then dyed for 30 min; this difference mainly arose from the difference in surface roughness. Although the bamboo green layer was completely removed in both groups, the 3–4 g removal group was treated with sandpaper of a higher mesh number, and therefore had a lower surface roughness. According to the Wenzel model, a lower roughness leads to relatively poorer wettability; at the same time, a lower roughness also implies fewer dye adsorption sites and a smaller effective contact area. These factors together resulted in a slightly lower dye penetration depth.

3.8 Light fastness

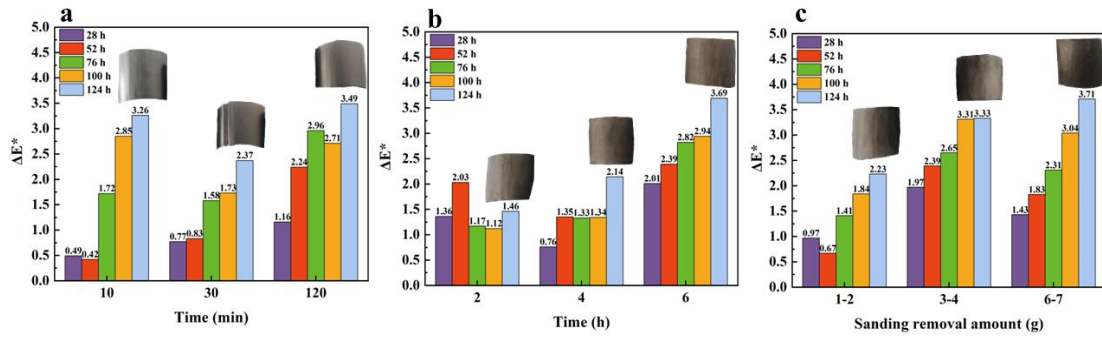


Fig. 9 Total color difference of dyed bamboo samples with varying xenon lamp irradiation time: (a) untreated samples with dyeing duration of 2 h, 4 h, and 6 h, respectively; (b) samples sanded with 180-grit with dyeing duration of 10 min, 30 min, and 120 min, respectively; (c) dyed samples with sanding removal amount of 1–2 g, 3–4 g, and 6–7 g, respectively

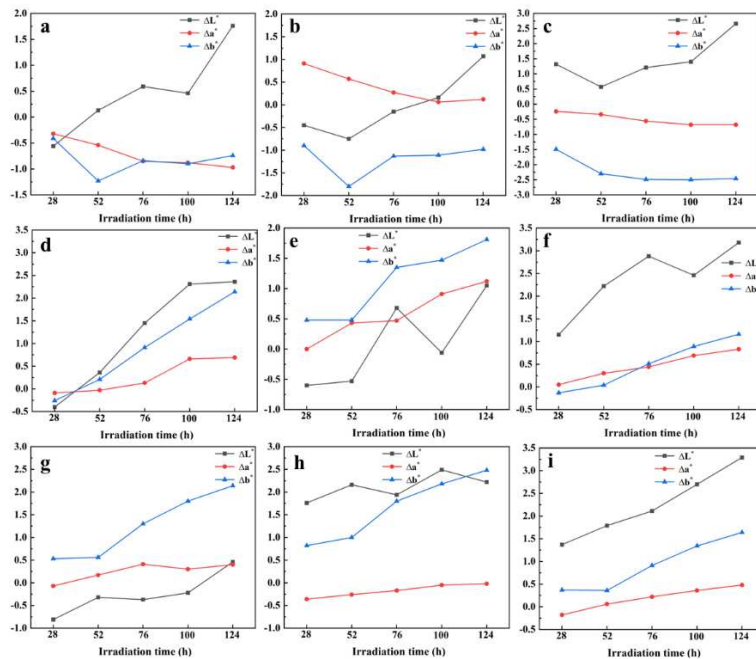


Fig. 10 ΔL^* , Δa^* and Δb^* values of dyed bamboo: (a–c) untreated samples with dyeing duration of 2 h, 4 h, and 6 h, respectively; (d–f) samples sanded with 180-grit

with dyeing duration of 10 min, 30 min, and 120 min, respectively; (g–i) dyed

samples with sanding removal amount of 1–2 g, 3–4 g, and 6–7 g, respectively

As shown in the Fig. 9 and 10, the results of the light fastness tests for dyed bamboo culms without treatment, dyed bamboo culms with sanding treatment, and dyed bamboo culms with different sanding removal amounts are presented respectively.

During the light fastness test, the luminosity and total color difference of almost all dyed bamboo culm samples showed an increasing trend, indicating that the surface color of the dyed bamboo culms fades, became whiter and brighter, and the total color difference increases with the extension of xenon lamp irradiation time. This is because the surface color of undyed bamboo is relatively light. Under light exposure, the molecular structure of the dye on the bamboo surface is destroyed, causing the color of the dyed bamboo to become lighter and brighter and the total color difference to increase (Divya et al. 2025). In addition, the surface lignin exhibits high sensitivity to ultraviolet (UV) radiation, being the first component to absorb UV energy and undergo oxidative degradation, resulting in color changes (Jia et al. 2024). Visual observation of the dyed samples after 124 h of xenon lamp irradiation revealed that compared with the samples dyed directly without sanding, the dyed bamboo culms subjected to sanding treatment exhibits poorer light resistance and was more prone to fading, indicating that sanding treatment had a negative effect on the color stability of bamboo culms. Overall, based on the figures, the dyed bamboo culms with a sanding removal amount of 6–7 g

507 showed the largest color difference change after 124 h of irradiation, reaching 3.71. For
508 the untreated dyed bamboo culms showed that the total color difference of samples dyes
509 for 2 and 4 h changed slightly with prolonged xenon lamp irradiation, while those dyes
510 for 6 h exhibited a larger variation in total color difference. For the sanded dyed bamboo
511 culms with different dyeing time revealed that the sample dyed for 30 min showed the
512 smallest total color difference change, the best stability, and the highest resistance to
513 fading. Analysis of the results for dyed bamboo culms with different sanding removal
514 amounts showed that the light fastness of the sample with a sanding removal amount
515 of 1-2 g is the best after 124 h of irradiation.

516 A comparison of the Δa^* and Δb^* values between unsanded and sanded dyed bamboo
517 reveals that both Δa^* and Δb^* in the unsanded samples decrease, whereas those in the
518 sanded samples increase. This indicates that prolonged xenon irradiation drives
519 unsanded dyed bamboo toward green and blue hues, whereas sanded dyed bamboo
520 shifts toward red and yellow. Under xenon irradiation, Acid Red (monoazo) and Acid
521 Yellow (bisazo), are susceptible to photo-oxidative cleavage of the azo bond ($-N=N-$)
522 because of their azo structures, and therefore exhibit significantly lower lightfastness
523 than anthraquinone-based Acid Blue (Cho et al. 2023). As the yellow and red dyes
524 undergo extensive photodegradation and fading, the proportion of Acid Blue in the
525 color mixture rises sharply. As a result, the color shifts from greenish-blue further
526 toward greener and bluer tones.

In contrast, sanding removes the wax and silica layers, allowing the dye to penetrate more uniformly into the cell walls and pores rather than merely residing on the outermost surface. Therefore, during aging, surface color change is no longer solely governed by dye fading; it is also influenced by the photo-oxidation of the bamboo matrix. Concurrently, the sanded bamboo displays a pronounced color shift toward red and yellow. Lignin and other photolabile components in bamboo undergo photooxidation under xenon irradiation, yielding reddish ortho-benzoquinone and yellowish para-benzoquinone structures. Hence, sanded dyed samples are more susceptible to reddening and yellowing upon aging (Zhu et al. 2024; Kanbayashi et al. 2018). Sanding exposes additional hydroxyl groups and cell wall structures, thereby enhancing the dye–matrix interactions. Thus, during aging, oxidation of the bamboo matrix drives the overall color shift toward red and yellow, rather than being solely attributable to dye fading.

Although the 2 h dyed unsanded samples and bamboo culms with a sanding removal amount of 1-2 g exhibited relatively better light fastness, uneven surface color distribution was observed before the test. Comprehensive evaluation considering both the light fastness of dyed bamboo culms and the uniformity of surface color before the test showed that the 4 h dyed unsanded samples, 30 min dyed sanded samples, and the dyed samples with a sanding removal amount of 3-4 g had relatively good comprehensive performance.

4 Conclusion

In this study, the effects of bamboo green layer sanding treatment, dyeing duration, and sanding removal amount on the dyeing performance of Moso bamboo culms were systematically investigated. Based on the research results, sanding treatment of bamboo culms significantly decreased Si content, increased surface roughness and wettability, and caused damage to surface cell structures, with exposed cell lumen of the cells and pits on the cell walls, which promoted dye adhesion and transverse penetration of dye liquids into the bamboo culms. Moreover, owing to Jurin's law, the dye adsorption rate of the bamboo was significantly improved. With the increasing sandpaper grit size, the sanding marks on the bamboo surface weakened and the roughness decreased. After dyeing, the surfaces of the samples showed a significant color difference from undyed bamboo, with a uniform dark green appearance. Sanding treatment greatly shortened the time required for uniform dyeing and improved dyeing efficiency; dye penetration depth and color depth increased with extended dyeing time and higher sanding removal amount. Both sanding and dyeing reduced bamboo surface gloss, with unsanded dyed samples retaining higher gloss than sanded dyed counterparts. During the dyeing process, the dye adhered to bamboo surface via physical absorption, without forming new chemical bonds, showing a slight increase in the water contact angle. Sanding treatment negatively impacted the light fastness of dyed bamboo. Among the dyed bamboo culms, better light fastness

568 was obtained for unsanded bamboo dyed for 4 h, sanded bamboo dyed for 30 min,
569 and bamboo with 3-4 g sanding removal amount.

570 Nevertheless, limitations still remain in this study since manual sanding has
571 significant variability in terms of applied pressure, feed speed, and treatment
572 uniformity. The automated mechanical sanding device will be adopted to improve
573 sanding efficiency and consistency in future research. Overall, this study proposed a
574 practical pretreatment method for bamboo culm dyeing, which offers theoretical and
575 technical support for the high-value utilization of bamboo.
576

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