Flattened Bamboo for Replacing Plastic Products – An Eco-friendly Material to Manufacture Clothes Hangers

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Plastic waste is increasing year by year, and its non-degradable nature is causing great damage to the environment. Bamboo is an environmentally friendly and sustainable material. Flattened bamboo green slices offer an alternative solution to plastic hangers due to their excellent bending-mechanical properties. This study elaborates a production technology for flattened bamboo green hangers (FBGH), as well as the status changes of bamboo and related quality issues during the production process. To reveal patterns of bamboo performance variation throughout the bamboo hanger processing, this study analyzes the temperature, moisture content, and thickness changes of bamboo during production. Additionally, key quality issues in the process include cracking, thickness uniformity, and paint film performance. The results indicate that the main quality issues were cracking and thickness uniformity of bamboo green slice. The splitting process significantly affected the thickness uniformity of the bamboo green slice. The cracking of flattened bamboo green slices was most occurred in the splitting, cold pressing, and drying processes. Optimizing the management of the process, improving slicing equipment, minimizing the time between slicing and cold pressing, and adjusting lacquer film process parameters can enhance bamboo processing performance.

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INTRODUCTION

Plastic waste has been increasing year by year (Fig. 1a). Relevant statistics indicate that the world has cumulatively produced more than 460 million tons of plastic products from 2000 to 2019, of which only 9% were recycled (Shen *et al.* 2024; Fig. 1b). China is a leading producer of plastics, and discarded plastics pose significant environmental challenges, including increased landfill pressure, marine pollution, and resource depletion (Ren *et al.* 2018). In 2021, ten Chinese ministries and commissions, including the National Forestry and Grassland Administration and the National Development and Reform Commission, jointly issued the Opinions on Accelerating the Innovative Development of the Bamboo Industry (Xie *et al.* 2024). Subsequently, in 2023, agencies such as the National Development and Reform Commission introduced the Three-Year Action Plan to Accelerate Bamboo as a Substitute for Plastic. This initiative has paved the way for new opportunities in sustainable development (Geng 2023). In response, some companies have started promoting environmentally friendly bamboo as a viable alternative to plastic (Fig. 1c).

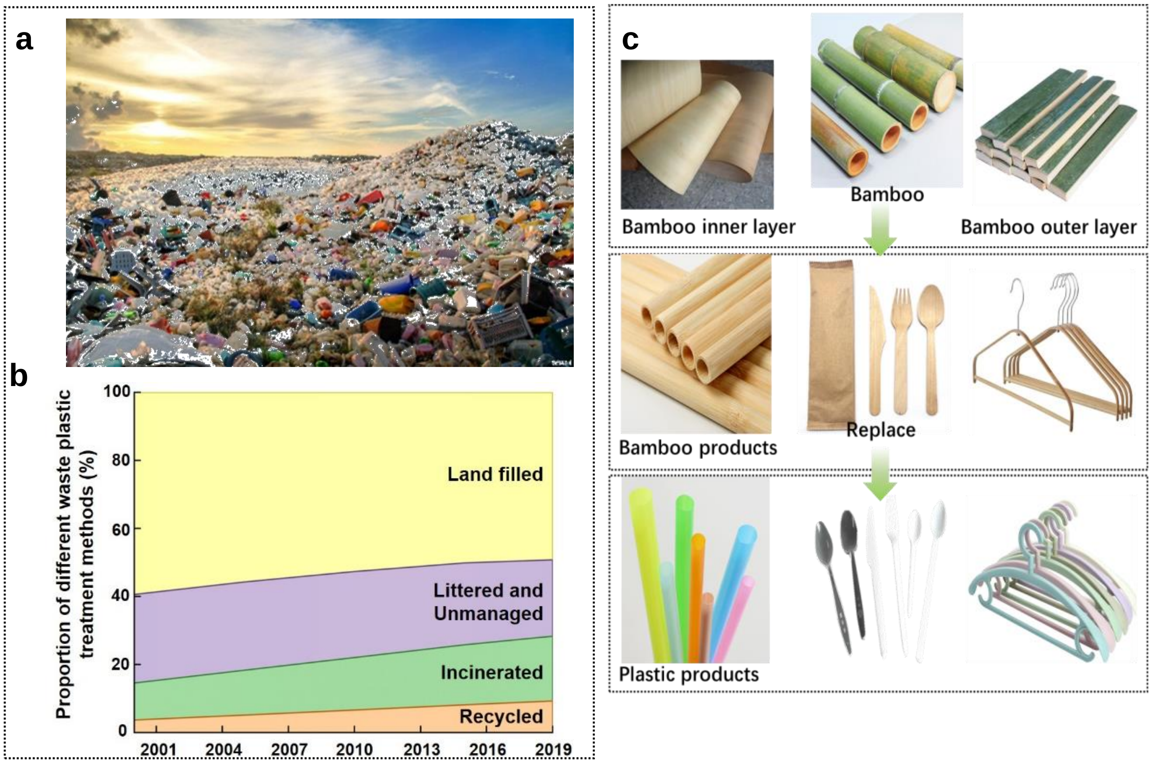

Fig. 1. Plastic pollution problem and bamboo plastic replacement program. a) Plastic pollution, b) Proportion of different waste plastic treatment methods from 2000 to 2019, c) Bamboo products as alternatives to plastic products (Data source: OECD 2023)

Bamboo is a renewable resource with heterogeneous properties. Based on its gradient structure, bamboo can be categorized into three distinct layers: the outer layer (bamboo green), the middle layer (bamboo flesh), and the inner layer (bamboo yellow). One key technological advancement in optimizing bamboo utilization is the bamboo flattening processing, which has rapidly developed and undergone technological iterations since 1999 (Li and Lou 2021; Lou *et al.* 2021). Flattened bamboo retains its natural texture, and the refinement of flattening techniques has enabled its efficient use in various industries, including bamboo cutting boards, flooring, furniture, and everyday items (Chen *et al.* 2021; Zhang *et al.* 2021). Bamboo flattening technology has been continually evolving over the years. Initially, due to the limitations of processing equipment and techniques, the layered utilization of bamboo based on its gradient structure was not considered. During the production process, the green and yellow layers are mostly removed before flattening, resulting in a low utilization rate of bamboo materials. Nowadays, modern technology can preserve the green layer for flattening, resulting in green-preserved flattened bamboo boards with significantly improved mechanical strength and weather resistance. Afterwards, through the splitting process, the bamboo green slices can be split and peeled off from the green-preserved flattened bamboo board and used for the production of bamboo green products. However, during the processing of bamboo green slices, issues such as cracks and deformations frequently occur, and this can directly impact the quality and aesthetics of the products. Enhancing the production process to improve the final product quality while preserving the natural characteristics of bamboo green slices remains a major challenge in flattened bamboo production (Li *et al.* 2016).

Bamboo green is an ideal material for producing hangers due to its high fiber density, hardness, and flexural properties (Li *et al.* 2013; Qin *et al.* 2024). Based on bamboo flattening technology with bamboo green preservation, this study outlines a production process for hangers, which are called flattened bamboo green hangers (FBGH). By employing process technologies such as saturated high-pressure and high-temperature steam softening, cold press shaping, and vacuum drying, issues such as cracking and deformation in bamboo green slices can be reduced. To better understand the production process, this study explored the relationship between each production step and associated quality issues, as well as the underlying causes of these problems. It investigated the material flow of bamboo during the production of FBGH, directly reflecting how process parameters affect product quality. This study aimed to provide scientific evidence to support the production of FBGH and offer valuable insights for the manufacturing of other bamboo products.

PRODUCTION PROCESS OF FLATTENED BAMBOO GREEN HANGER

According to the material form during the production process, the production of FBGH can be divided into two parts. The first part is the processing flow of the flattened bamboo green slice, which includes softening, removing the bamboo yellow layer, arc milling, flattening, splitting, cold pressing, and drying. The second part is the molding process of the flattened bamboo green hanger, which includes surface treatment of the dried bamboo green slice (band sanding, planing, roller sanding), gluing, molding, drilling, coating and assembling (Fig. 2).

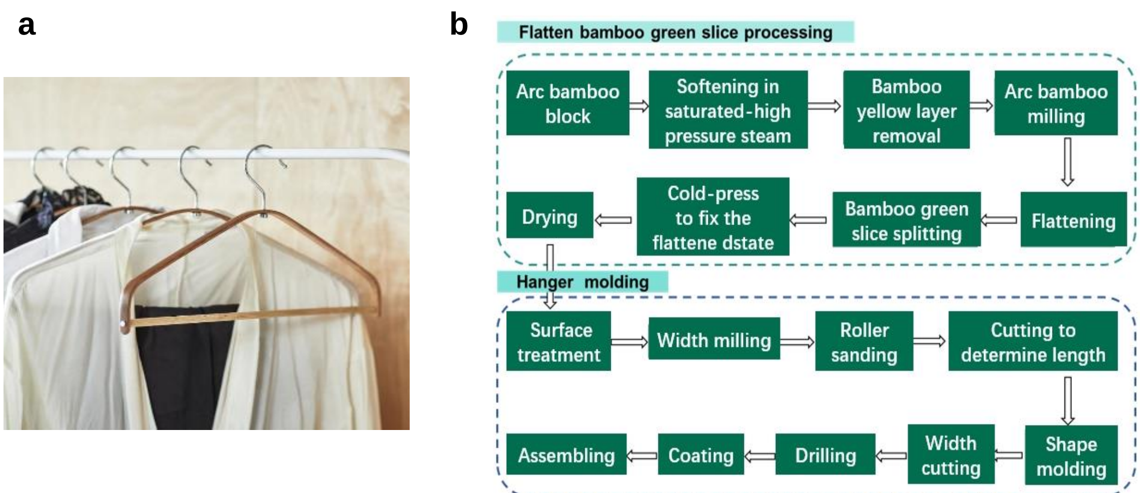

Fig. 2. Process for flattened bamboo green hangers (FBGH). a) products, b) the main procedures

Flattened Bamboo Green Slice Processing

Raw material

The main raw material was *Phyllostachys pubescens* with DBH of 8.5 to 10.5 mm and bamboo age of more than 5 years. Bamboo cut at a distance of more than 1 meter from the root was used to produce clothes hangers. The surface of the selected bamboo was free from noticeable defects, such as moth damage, and the material was uniform. The density of bamboo was approximately 0.72 g/cm ³.

Preprocessing

The preprocessing stage comprises four main steps: bamboo tube cutting, diameter grading, bamboo block splitting, and bamboo node removal.

Initially, the raw bamboo was segmented into lengths of 1150 mm. Subsequently, the bamboo segments were assessed for wall thickness, ranging from 8.5 to 10.5 mm, and categorized into two diameter grades: 8.5 mm to 9.5 mm and 9.5 mm to 10.5 mm (Fig. 3a). Bamboo tubes within each grade were then split into arc-bamboo blocks (Fig. 3b), ensuring a minimum width of 110 mm to minimize processing waste and optimize flatten efficiency.

The internal nodes and external nodes of the arc-bamboo block were removed sequentially (Fig. 3c).

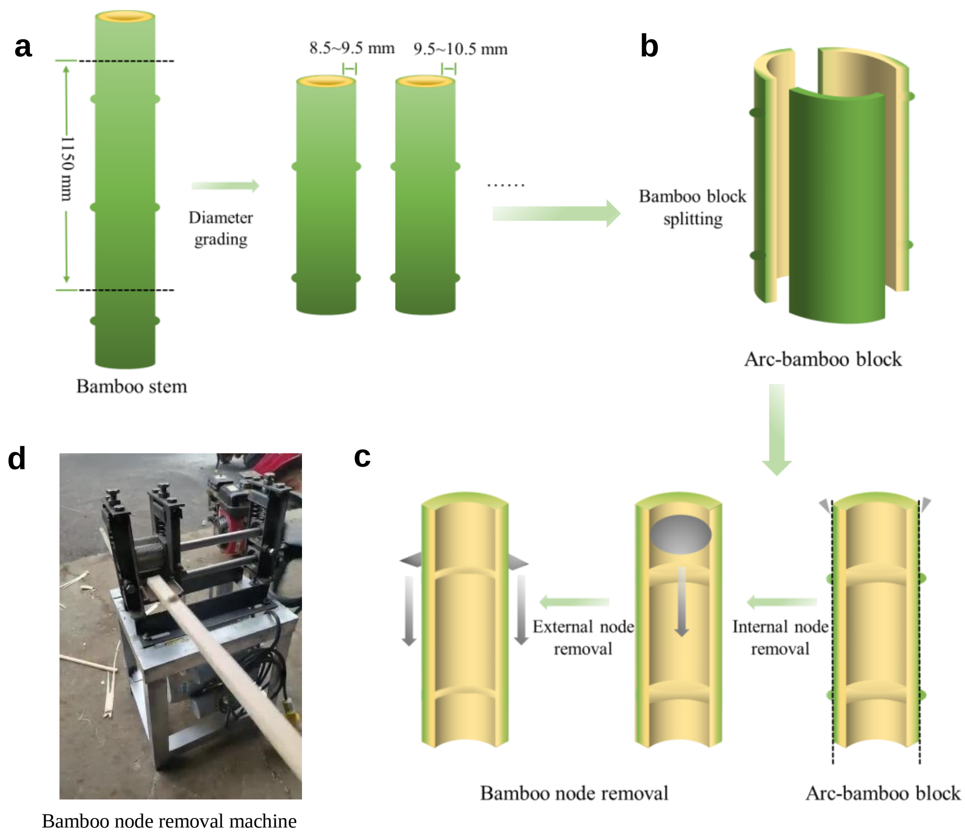

Fig. 3. Bamboo preprocessing. a) bamboo tube grading, b) arc-bamboo block splitting, c) bamboo node removal, d) bamboo node removal machine

Softening

Bamboo softening was carried out using a high-temperature steam softening technique, which is currently the most environmentally friendly and cost-effective treatment method. It usually utilizes saturated steam at temperatures ranging from 120 to 220 °C (Zhang *et al.* 2013; Wang *et al.* 2020a; Wang *et al.* 2020b), thereby maintaining the physical and mechanical properties of bamboo, providing rapid and effective softening, and providing a process suitable for large-scale production.

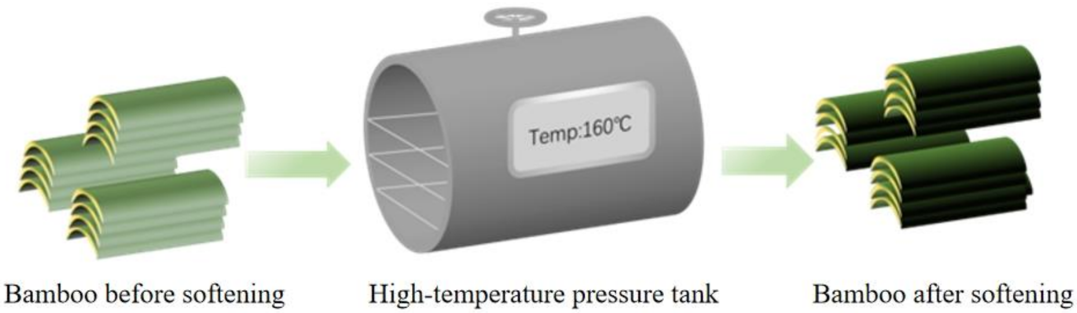

Fig. 4. Softening of arc-bamboo block

The softening processing utilizes arc-bamboo blocks with approximately 30% moisture content (Lou *et al.* 2022). The tank temperature was set at 160 °C (Fig. 4). The heat treatment duration for bamboo blocks in the tank was determined by the thickness of the bamboo walls. For an 8.5 mm thick bamboo block, a treatment time of 300 seconds is recommended, with an additional increase of 30 to 40 seconds for every extra 1 mm in thickness (Table 1). This was performed to enhance softening quality and ensure that softened bamboo block possess a sufficiently high moisture content to enhance their plasticity during flattening.

Table 1. Softening Time of Arc-bamboo Block with Different Wall Thickness

Bamboo Wall Thickness (mm)	Softening Time (s)
8.5	300
9.5	330-340
10.5	360-380

Bamboo yellow layer removal and arc-bamboo milling

After softening, it is imperative to promptly process the arc-bamboo block to remove the bamboo yellow layer (Pan 2018). Typically, the removal thickness of bamboo yellow layer is around 2 mm (Fig. 5a). The suggested feeding speed is 18 m/min.

Subsequently, the arc-bamboo block was promptly introduced into the curvature milling machine. Here, it underwent trimming and arc adjustment using the arc-shape planer knife to ensure uniform curvature on both surfaces of the bamboo block, and the milling knife was employed to ensure compliance with specified width requirements for post-processing steps such as splitting and flattening (Fig. 5b). The suggested feeding speed was 27 m/min.

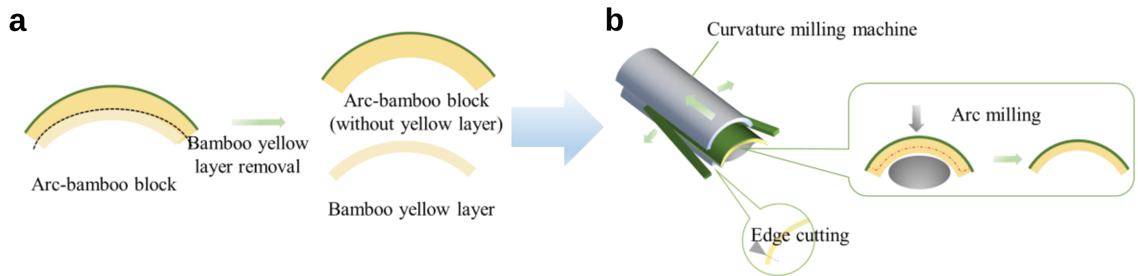

Fig. 5. Bamboo yellow layer removal a) and arc-bamboo milling b)

Flattening

In the production of flattened bamboo green hangers, the no-notch bamboo flattening technology was employed, wherein the step of removing the bamboo green layer was omitted, thus further optimizing the bamboo utilization efficiency (Lin *et al.* 2015; Li *et al.* 2020). During the procedure for flattening arc-bamboo block (Fig. 6a), it is critical to maintain the temperature of the bamboo above 80 °C to prevent cracking during flattening. The flattening process took approximately 8 seconds, followed by a 1-second shaping fix of the pressure material to ensure the bamboo remained flat. After the flattening, the width of the bamboo piece measured approximately 110 mm. The squeezing effect during the flattening process resulted in some water loss from the bamboo.

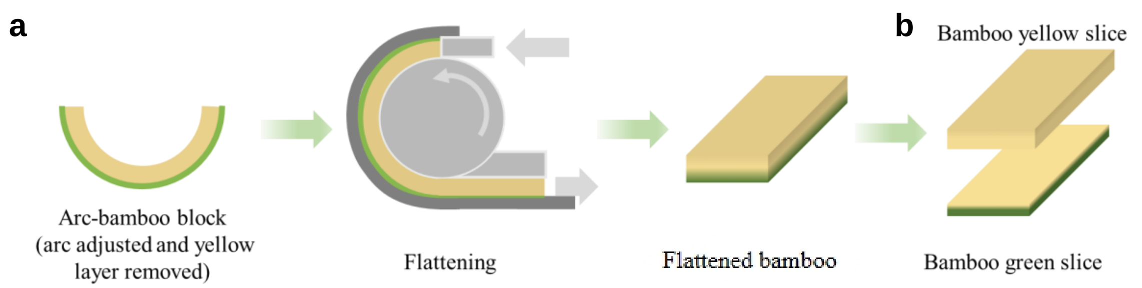

Fig. 6. Bamboo flattening a) and bamboo green slice splitting b)

Bamboo green slice splitting

The hot splitting technique was used for the production of FBGH. The flattened bamboo pieces, which remained above 70 °C after the flattened process, were split into two parts, the flattened bamboo green and yellow slices (Fig. 6b). The flattened bamboo green slices were utilized for subsequent processing to manufacture FBGH. Typically, the thickness of the flattened bamboo green slice, around 2.8 mm, meets the requirements for further processing. However, in actual production, issues such as uneven thickness and cracking may arise after splitting, leading to variations in wall thickness of the flattened bamboo green slices. To accommodate subsequent drying and sanding processes adequately, the average thickness of the flattened bamboo green slice was approximately 3.1 mm.

Cold-press

After splitting, the flattened bamboo green slice was subjected to pressing at room temperature to fix flattened status and prevent the arc spring-back. This process comprised four steps: grade sorting, bundling, pressing, and stacking. Based on the quality of the flattened bamboo green slice, it is typically categorized into two grades, each intended for the production of corresponding grade hangers. Every 8 pieces of flattened bamboo green slice were bundled together, with three loops tied along the length using a bundling machine (Fig. 7a) and then pressed for 8 h at room temperature. Subsequently, the bundles were crisscross stacked, with weights placed atop the stacks for a designated period to ensure the flattened bamboo green slice remained flat (Liao and Jin 1995), thus releasing any internal stresses (Fig. 7a).

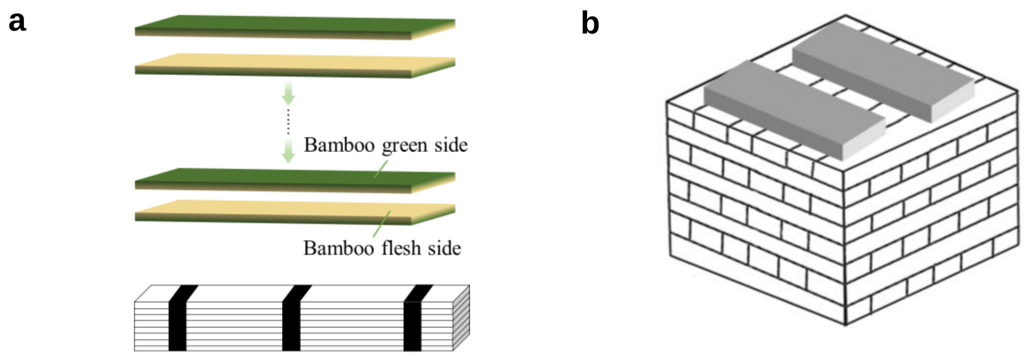

Fig. 7. Bamboo green slice bundling a) and stacking b)

Drying

The production of bamboo green hanger employs superheated steam drying technology. Superheated steam drying technology utilizes the unsaturated properties of superheated steam to extract moisture from the bamboo's surface upon contact, facilitating dehydration and drying processes (Liu 2016; Su *et al.* 2020). Integrating this technique with vacuum drying can enhance drying efficiency, reduce costs, conserve energy, and mitigate environmental impacts, rendering it suitable for large-scale production (Liu 2009).

Throughout the drying procedure, real-time monitoring of the moisture content of the flattened bamboo slices is conducted to regulate the drying progress. Once the final moisture content reaches 13%, the drying equipment initiates preheating to 58 °C, maintaining it at 60 °C for 1 h, then proceed with the programmed drying procedure of the flattened bamboo green slices (Table 2). Upon reaching the desired moisture content, the heating program ceases, and the equipment undergoes a 4-h cooling period to reach 40° C, thereby completing the drying process.

Table 2. The Superheated Steam Drying Procedure of Flattened Bamboo Green Slice

Moisture content (%)	Temperature (°C)	Pressure (KPa)
＞50	64	18
35~50	68	21
30~35	70	21
25~30	72	21
20~25	70	20
10~20	70	20

Molding Processing

Surface treatment

The process involved three stages: sanding, planing, and roller sanding.

To remove the wax on bamboo green layer, the flattened bamboo green slices were fed into the sander machine with the bamboo green skin facing upwards. The sander was equipped with three sanding belts with grain size of 120#, 180#, and 180#, respectively (Fig. 8a). The sanding process was carried out to achieve a target final thickness of 2.5 mm.

Following the sanding of the bamboo's green skin, the flattened bamboo green slices were fed into the planing machine with the bamboo flesh side facing upwards. The planing knifes were used to mill the bamboo flesh side and adjust the width of the bamboo green slice to ensure a uniform edge (Fig. 8b). The planing machine was configured to achieve a target final thickness of 2.1 mm, with a machining allowance of 1mm in the width direction.

Following planing, the flattened bamboo green slices were fed into the roller sanding machine with bamboo green skin facing upwards. The bamboo green skin was subjected to roller sanding to ensure a smooth surface devoid of any waxy residue. The roller sander consisted of 6 abrasive brush rollers, with the first five rated at 60# and the last one at 80# (Fig. 8c).

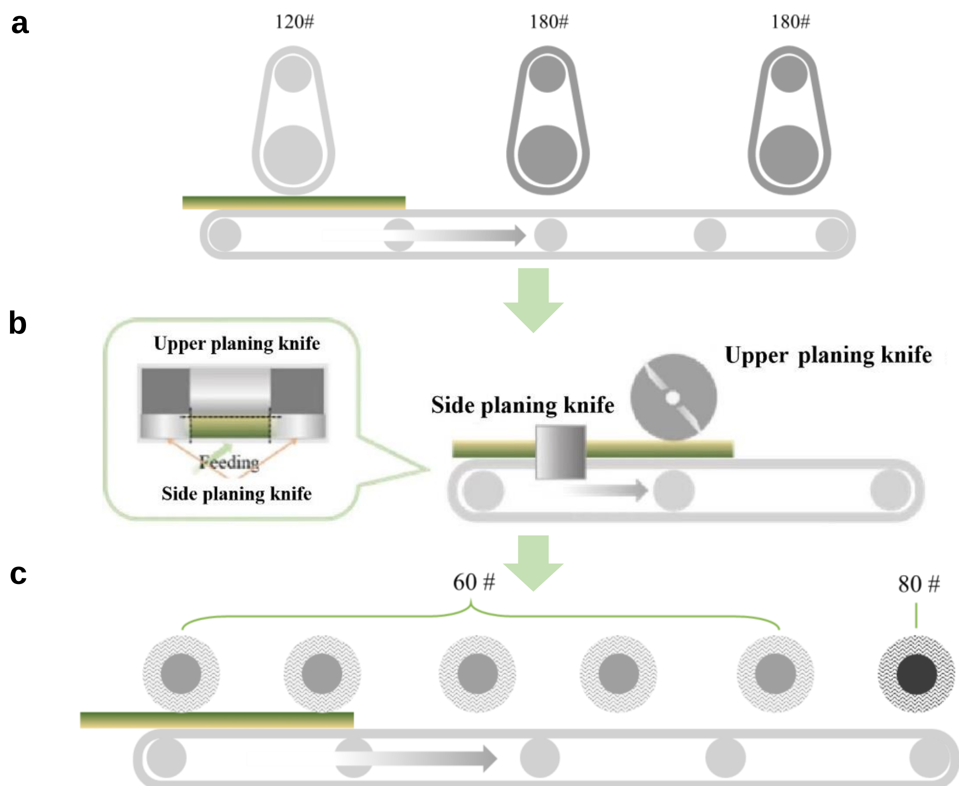

Fig. 8. Surface treatment. a) belt sanding, b) planing, c) roller sanding

Molding

The mold-manufacturing process involves several steps: length cutting, glue coating, molding, and single hanger split.

Length cutting involves using a saw to divide the surface-treated bamboo green slice into two pieces to achieve the required length for the hanger. Post-cutting, the bamboo green slice measured 545 mm × 110 mm × 2 mm (Fig. 9a).

The subsequent step was glue-coating (Melamine Urea-Formaldehyde Resin, AIBON P-4610, AICA Asia Pacific Holding Pte. Ltd.). Initially, the surface of the cut bamboo green slices were cleaned. Subsequently, bamboo flesh sides of the slices were glue-coated and stacked together, aligning flesh side to flesh side (Fig. 9b).

Next, hanger molding was done. The glue-stacked bamboo green slices were loaded into the hot press cooling and setting machine, where the temperature for hot pressing molding was maintained at 105 °C for 2.5 min. Following cooling setting, the bamboo green slices were well shaped, resulting in a molded board with a thickness of 4 mm (Fig. 9c).

Finally, single clothes hangers were obtained by dividing the structure in the width direction. This step was done with a cutting-milling-chamfering integrated machine. Initially, the well-pressed curved hanger board was cut along the width direction to split the material into single hangers. Subsequently, the hanger ends were milled into a round shape, followed by chamfering along the length of the hangers. After these processes, the dimensions of the bamboo green hanger were 400 mm × 12 mm × 4 mm (Fig. 9d).

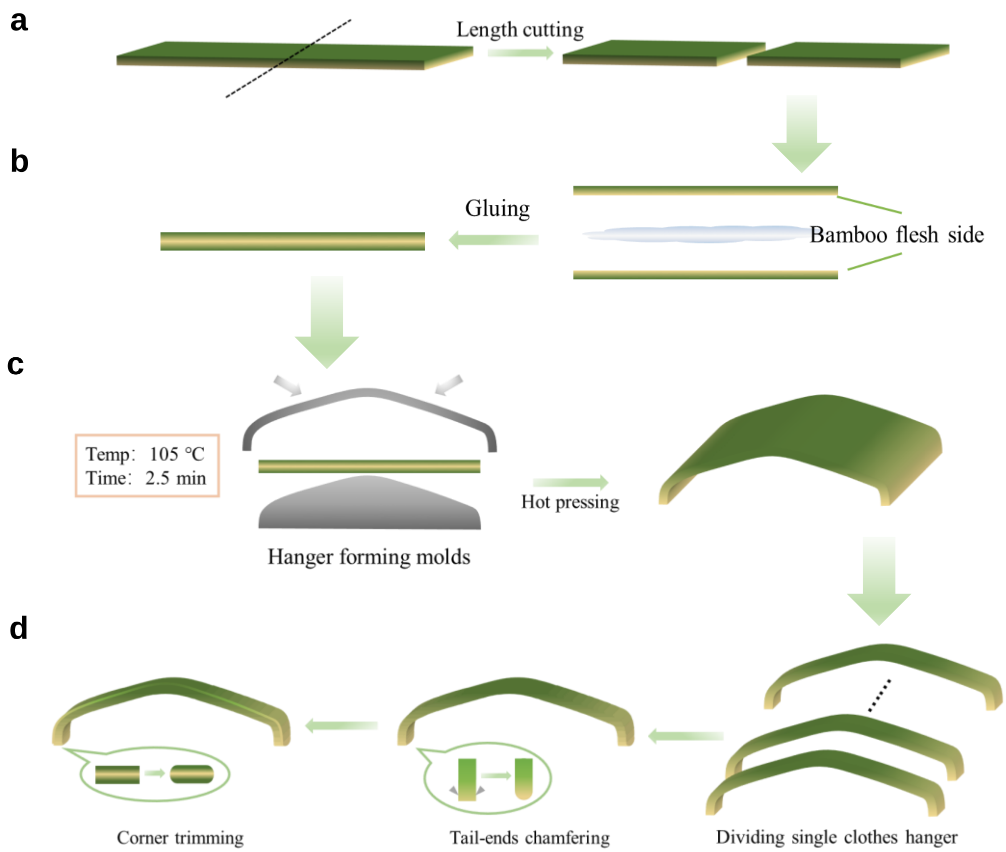

Fig. 9. Shaping of flattened bamboo green hangers (FBGH). a) length cutting, b) gluing, c) molding, d) single-hanger splitting and ends adjusting

Post-molding processing

The subsequent processes were mainly drilling, painting, and assembling.

For the hole punching process, the hangers were sequentially placed into the drilling machine, where holes were drilled in the middle and both ends of the hangers. The hole diameter measured 3.8 mm in the middle and 3 mm at the ends (Fig. 10a).

For the painting process, the hangers were batch processed with clear varnish by spraying coating (Fig. 10b). Initially, a layer of primer was applied. After allowing it to dry for 6 hours, a grinder or sandpaper was used to sand and trim the rough parts. Subsequently, the top paint was applied and left to dry for 24 hours.

During the assembling process, the coated bamboo green hanger shoulder pieces were assembled with metal hooks and bamboo crossbars (Fig. 10c), and then packaged for storage (Fig. 10d).

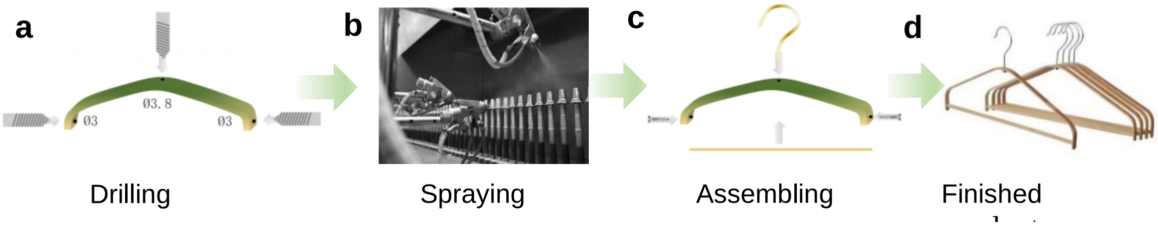

Fig. 10. Post-molding processing. a) drilling, b) spraying, c) assembling, and d) finished product

MATERIAL FLOW IN FLATTENED BAMBOO GREEN HANGER PROCESSING

Material flow refers to the status change of raw materials throughout various production processes. Monitoring of these status changes is crucial for controlling and improving the final product's quality. In the production of flattened bamboo green hangers, three key parameters—temperature, moisture content, and thickness—play a vital role in the bamboo processing flow.

Temperature

Significant temperature fluctuations occur during the softening, removing bamboo yellow layer, arc milling, flattening, and splitting stages. The high-pressure saturated steam creates a high-temperature, high-humidity environment, which enhances the plasticity of the bamboo blocks for subsequent processing (Huang *et al.* 2016; Chen *et al.* 2022). After softening, the average temperature of the bamboo blocks was around 99 °C. As the processing continued, the temperature gradually decreased, and the bamboo's plasticity correspondingly diminishes (Fig. 11). It is necessary to complete the splitting stages at a temperature of about 70 °C or higher.

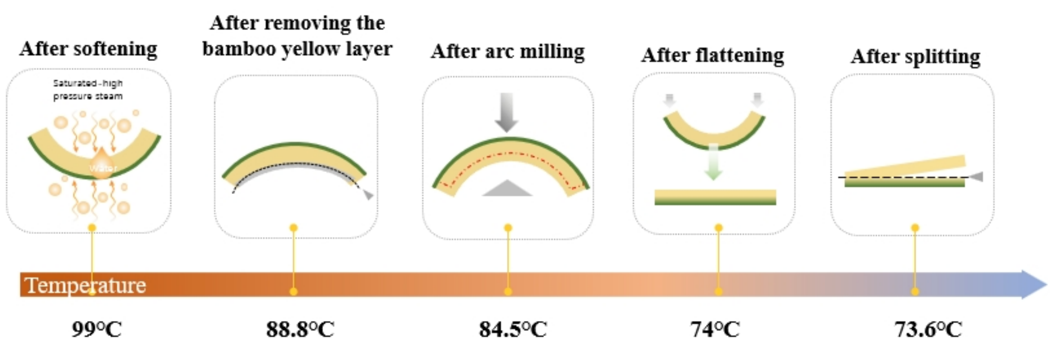

Fig. 11. Changes of temperature in flattened bamboo green slice production

Moisture Content

Moisture content is a crucial indicator of the mechanical properties of bamboo (Ribeiro *et al.* 2017; Liu 2021). During the production of flattened bamboo green hangers, changes in bamboo moisture content mainly occur during the softening, remove bamboo yellow, arc milling, flattening, splitting, and drying processes (Fig. 12). The average moisture content of the arc bamboo blocks before softening was 27.5%. After softening, the average moisture content increased to 67.9%. The bamboo yellow layer removal and arc milling processes had minimal impact on moisture content. However, during the flattening process, moisture content significantly decreases to 42.5% due to the squeezing effect on bamboo, which densifies the fiber and parenchyma cells, reducing the exchange channels for water molecules (Yu *et al.* 2021). The splitting process separates the bamboo green from the flattened bamboo, with the rest of the flattened bamboo retaining a higher moisture content and the green bamboo a lower one. Consequently, the average moisture content of the bamboo green slice dropped to 24.4%. After drying, the average moisture content of the flattened green bamboo slice was 12.5%. This reduction in moisture content increases the density of the bamboo cell walls (Guan *et al.* 2003; Chen *et al.* 2018), imparting higher elasticity and hardness to the flattened green bamboo slices, which is beneficial for subsequent surface treatments.

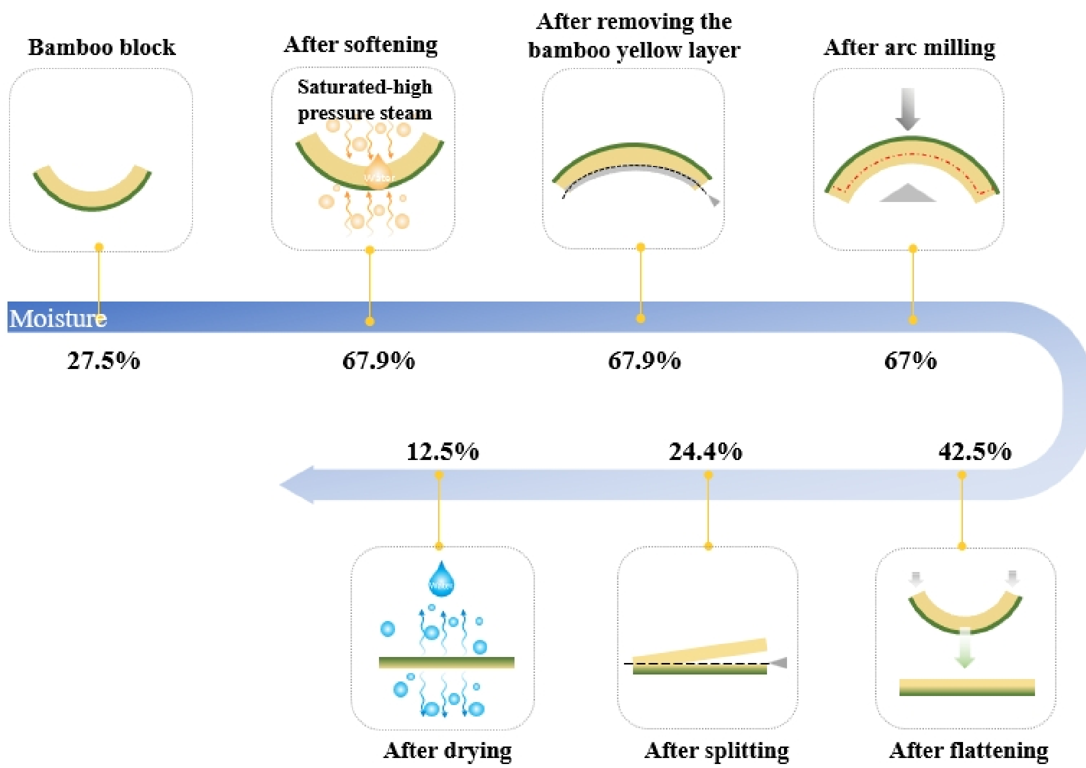

Fig. 12. Changes of moisture content in flattened bamboo green slice production

Thickness

To meet product thickness specifications, the thickness of the flattened bamboo green slices must be precisely adjusted during production. The process of thickness variation and the associated steps in manufacturing FBGH are as shown in Fig. 13. After softening treatment, the bamboo absorbs water and swells, increasing the thickness to 10.3 mm. Upon splitting, the green and yellow parts of the bamboo were separated, allowing them to be used according to their distinct gradient structures and physical properties. Post-drying, the anisotropic nature of bamboo caused radial shrinkage, further reducing the thickness of the green bamboo slices. Finally, the band sanding, planing, and roller sanding processes eliminated the surface wax layer from the flattened bamboo green slices, bringing the final thickness down to 2.1 mm.

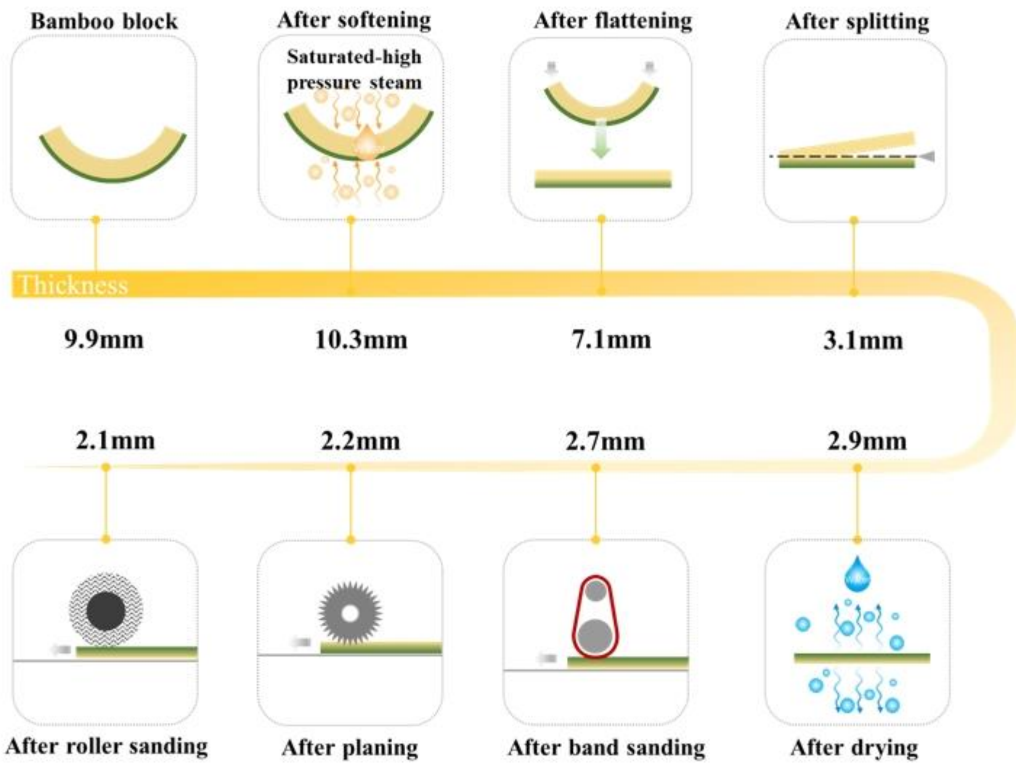

Fig. 13. Changes of thickness in flattened bamboo green slice production

Surface Roughness

Surface roughness directly impacts the coating quality of outer skin and the gluing performance of inner pith of bamboo hangers (Xu *et al.* 2024). As illustrated, R_a denotes the average surface roughness (Fig. 14a), and R_z represents the maximum height of surface roughness (Fig. 14b), both of which common parameters for assessing surface texture (Varga *et al.* 2024).

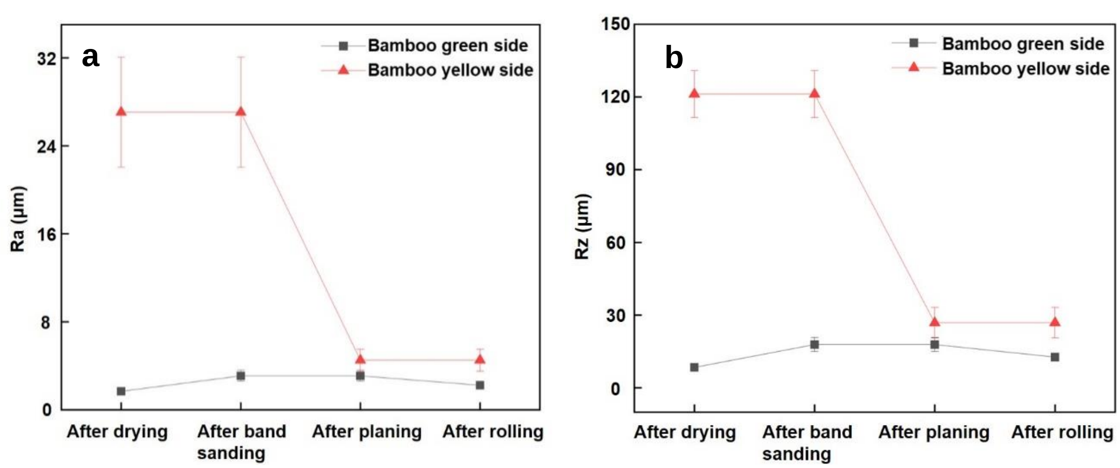

Fig. 14. The surface roughness of bamboo in different processes: (a) R_a, and (b) R_z

Generally, the roughness of the bamboo outer skin was significantly lower than that of the bamboo inner pith. This is due to the higher fiber density and the presence of a smooth wax layer on the bamboo green surface, making it initially very smooth. To enhance the finishing process, the wax layer was first removed using wide belt sanding, which roughens the surface. This was followed by roller sanding to reduce the roughness. Consequently, the roughness initially increased after wide belt sanding and then decreased after planing.

Inner pith's roughness sharply declines after planing, as the grooved contours on inner pith after splitting (Yang *et al.* 2008) cause high R_a and R_z values. Planing smoothed these contours. Consequently, the roughness gap between the green and yellow layer diminished, leading to a more uniform surface and better conditions for subsequent finishing.

PRIMARY QUALITY ISSUES IN PROCESSING

During the processing, as the bamboo status changes in the course of the machining processed, three main quality issues emerged in the production of flattened bamboo green hanger. These included cracking of the bamboo material, thickness inconsistency, and uneven paint film adhesion and surface condition.

Cracking

During the production of flattened bamboo hangers, bamboo green slices often crack during splitting, cold pressing, and drying, which significantly impacts both yield and quality. Analysis indicated that post-splitting, cracks predominantly measured 200 to 400 mm, with a notable number under 200 mm. Conversely, after cold pressing and drying, most cracks were under 200 mm, with a significant number exceeding 600 mm (Fig. 15a).

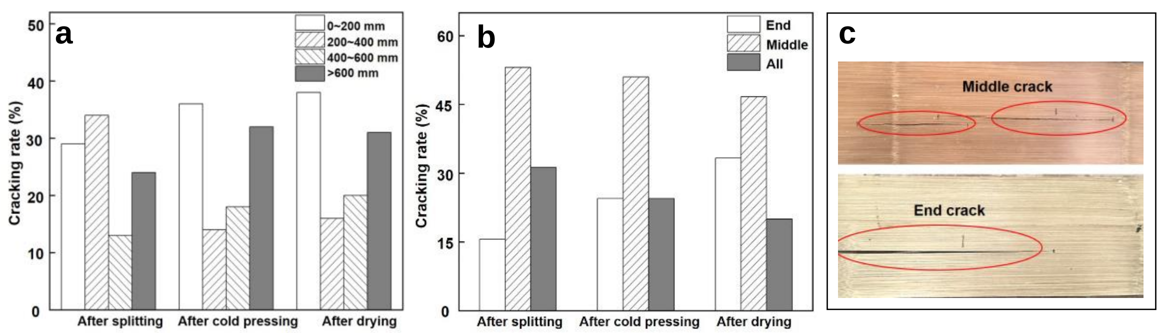

Fig. 15. The crack patterns and proportion of flattened bamboo green slices in process: (a) cracking rate of each length, (b) cracking rate of different forms, and (c) different forms of crack

In addition to crack length, the proportion of crack forms varied across each process (Fig. 15b, 15c). Among the three processes, the highest occurrence of cracks was in the middle of the bamboo green slices. This is because the middle part contains more bamboo nodes, where the fiber content is 1.7 times that of the internodes, increasing the likelihood of drying shrinkage and cracking (Zhou *et al.* 2003; Chen *et al.* 2016). As the bamboo strips progressed from splitting to drying, the proportion of cracks at the ends increased. This is likely due to rapid moisture loss from the ends, as the moisture content decreases, making them more susceptible to cracking.

Before splitting, bamboo underwent steam saturation, reaching a water-saturated status. After splitting, as bamboo green sheets awaited cold pressing and shaping, the gradual decrease in temperature and moisture content allowed for the release of internal residual stresses (Li *et al.* 2022; Roszyk *et al.* 2024). This release can cause bamboo green sheets to warp towards the bamboo inner pith. If internal stress is not effectively managed during cold pressing load application, the bamboo green sheets may crack, potentially leading to secondary cracking and crack propagation. There is a need to reduce the interface time between the profiling and the cold pressing process to minimize deformation and cracking caused by the reduced temperature.

Non-uniformity of Thickness

During the processes of splitting, drying, band sanding, roller sanding, and planing, the thickness uniformity of the flatten bamboo green slices changed. The thickness uniformity was poor during splitting, which affected subsequent processes such as drying and significantly impacted product quality. This variation is mainly related to bamboo joints, temperature, moisture content, and machining accuracy. To analyze the thickness variation of flattened bamboo slices at different stages of the production process, measurements were taken at nine distinct points (Fig. 16).

The initial thickness deviation of the bamboo green slices after splitting was significant, primarily due to the inherent uneven wall thickness of the bamboo material (Table 3). Additionally, improper control of temperature and moisture content during the softening process can lead to uneven softening of the bamboo green slices, resulting in uneven stress during flattening and an increased risk of warping before splitting (Qin *et al.* 2024).

After drying, the thickness of the flattened bamboo green slices decreased due to moisture content reduction, while the thickness deviation also decreased. This indicates that a proper drying process would help to enhance the flatness of the flattened bamboo green slices. Subsequent surface treatments, such as band sanding, planing, and roller sanding, further improved the thickness uniformity of the bamboo green slices.

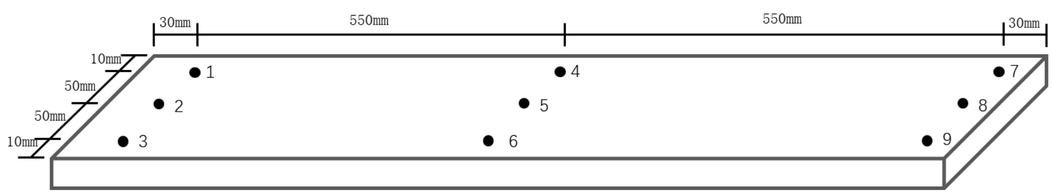

Fig. 16. Measurement point

Uneven Paint Film Adhesion and Surface Condition

The coating was primarily applied in the outer skin of the flattened bamboo green hanger. When the coating penetrates the bamboo surface, it forms a "swallowtail" structure (Rijckaert *et al.* 2001). Changes in the contact area between the coating and the outer skin can affect the adhesion of the paint film, thereby enhancing the aesthetics and extending the service life of the flattened bamboo slice (Chen *et al.* 2006; Lu *et al.* 2007; Xu *et al.* 2019a; Xu et al. 2019b). Before any surface treatment, the paint film adhesion on the bamboo outer skin was relatively poor (Table 4). After band sanding, the paint film adhesion, hardness, and surface condition of the bamboo outer skin improved significantly. However, compared to the status after band sanding, the paint film adhesion decreased following roller sanding, although hardness and surface condition continued to improve (Fig. 17).

Table 3. Thickness of Different Processes

Procedure	Thickness of each measuring point (mm)									Average Thickness (mm)
	1	2	3	4	5	6	7	8	9	
Splitting	3.06±0.27	3.05±0.26	3.12±0.24	3.06±0.20	3.10±0.26	3.05±0.28	3.08±0.31	3.05±0.33	3.10±0.36	3.0±0.25
Drying	2.73±0.27	2.75±0.30	2.74±0.30	2.71±0.36	2.73±0.29	2.72±0.43	2.81±0.36	2.80±0.35	2.85±0.36	2.86±0.21
Band sanding	2.64±0.14	2.56±0.14	2.65±0.17	2.74±0.23	2.74± .15	2.70±0.14	2.66±0.24	2.60±0.24	2.62±0.21	2.66±0.06
Planing	2.14±0.04	2.17±0.05	2.1 6±0.05	2.20±0.07	2.32±0.16	2.19±0.07	2.09±0.10	2.18±0.11	2.16±0.11	2.18±0.06
Roller sanding	2.08±0.09	2.12±0.10	2.09±0.10	2.12±0.07	2.22±0.13	2.14±0.09	2.09±0.06	2.16±0.10	2.11±0.11	2.12±0.04

a±-standard deviation.

Table 4. The Paint Film Performance of Bamboo Before and After Different Processes

Sample	Paint Film Adhesion (ASTM grade[a])	Surface Condition	
		Particles	Bubbling
Unprocessed	0B: 77% 1B: 17% 2B: 6%	0%	100%
Band sanding	4B: 20% 5B: 80%	20%	20%
Roller Sanding	3B: 23% 4B: 67% 5B: 10%	0%	0%

[a]Test standard of paint film adhesion GB/T 4893.4-2013 "Physical and chemical properties test of paint film on furniture surface Part 4: Cross-cutting method for measuring adhesion"; For each treatment process, 20 samples of flattened bamboo green slices were selected. The table presents the distribution of adhesion grades and surface conditions among these 20 samples.

Therefore, in the production of flatten bamboo green hangers, the surface treatment parameters for band and roller sanding must be carefully adjusted. The bamboo outer skin should not be excessively smooth, as this can weaken its bonding with the paint film, nor should it be excessively rough. Finding a balance in the surface treatment process is essential to optimize the overall performance of the paint film. Based on the research results of the paint film performance of the bamboo green clothes hangers and relevant experience, it is better to choose a grit level of 180 as the final grit number for sanding in order to achieve good adhesion to the coating.

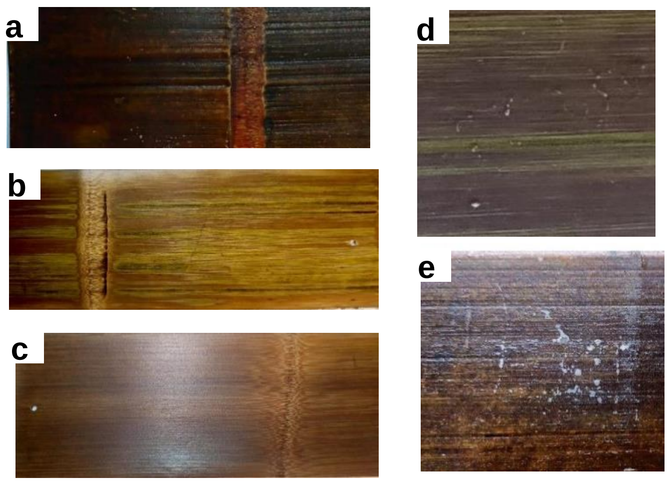

Fig. 17. The paint film performance of flattened bamboo green slices before and after different sanding processes: (a) Unprocessed, (b) Band sanding, (c) Roller Sanding, (d) Particles, and (e) Bubbling

CONCLUSIONS AND PROSPECTS

The preparation of clothes hangers from flattened bamboo provides a promising alternative to plastic products. While bamboo green is used for making hangers, the remaining parts of the bamboo can be used to produce other bamboo products, such as bamboo straws and forks. This process offers a way to fully utilize bamboo and provides a way to replace plastic hangers. However, shortcomings persist in the production process. In our opinion, the following specific opinions would offer new insights into the application of flattened bamboo.

1) To enhance the production efficiency and quality of flattened bamboo green slices, it is crucial to upgrade the production equipment. At the splitting stage, the uneven thickness of bamboo is primarily influenced by the natural wall thickness variations and limitations of the processing equipment, resulting in material wastage. Failure to apply cold pressing promptly after splitting causes the bamboo to bend and deform due to the release of internal stresses, which increases the likelihood of cracking in the flattened bamboo green slices. Therefore, it is essential to investigate methods for improving the sanding process to enhance lacquer film adhesion, develop new technologies to improve thickness uniformity post-splitting, and improve equipment integration.

2) Improving real-time monitoring and automation technologies is crucial for optimizing the entire production process of flattened bamboo green hangers. Throughout the production stages, factors such as temperature, thickness, and moisture content of the

FBGH fluctuate. Temperature control plays a key role in softening, flattening, splitting, and drying processes, while variations in thickness during splitting, drying, and surface treatment directly impact the cracking rate of the product. Additionally, moisture content during softening, splitting, and drying influences the plasticity of the bamboo and the overall quality of the final product. It is necessary to monitor product status changes for detecting production issues and to facilitate process optimization in time.

3) It is important to advocate for the use of bamboo materials and to promote environmental consciousness. To raise public awareness of bamboo's environmental advantages, collaborative efforts between businesses and governmental entities can be initiated to conduct environmental education campaigns. These initiatives aim to effectively communicate the eco-friendly nature of bamboo and the practicality of bamboo products, thus enhancing public understanding and acceptance of environmentally sustainable materials. Businesses can play a pivotal role by prominently featuring bamboo's environmental attributes in product packaging and promotional materials, thereby encouraging consumers to embrace greener lifestyles.

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REFERENCES CITED

Chen, F., He, Y., Wei, X., Han, S., Ji, J., and Wang, G. (2022). "Advances in strength and toughness of hierarchical bamboo under humidity and heat," *Journal of Forest Engineering* 8(4), 2096-1359. DOI: 10.13360/j.issn.2096-1359.202207008

Chen, L., Liu, H., Li, Y., Lou, Z., Lin, H., and Yang, F. (2021). "A study on manufacturing technique of crack-free flattened bamboo," *Forestry Science and Technology Communications* 3, 53-55. DOI: 10.13456/j.cnki.lykt.2020.03.29.0002

Chen, Q., Chen, M., and Fei, B. (2018). "A review on the influence of water on the mechanical properties of bamboo," *Journal of Bamboo Research* 37(02), 84-89. DOI: 10.19560/j.cnki.issn1000-6567.2018.02.014

Chen, Q., Wei, L., Miao, Q., Luo, X., Ma, X., Chen, L., and Huang, L. (2016). "Physical and chemical properties of different parts of green bamboo," *Trans. China Pulp Pap.* 31(3), 1-6. DOI: 10.3969/j.issn.1000-6842.2016.03.001

Chen, X., Shen, L., Huang, H., Lu, Z., Ye, H., and Wu, X. (2006). "How adhesion of water-based primer sealer affected by roughness of wooden surface," *Furniture* 2006(3), 45-47. DOI: 10.16610/j.cnki.jiaju.2006.03.003

Geng, G. (2023). "The global action of 'Replacing Plastic with Bamboo' kicked off," *Green China* 21, 8-13. DOI: 10.3969/j.issn.1672-7789.2023.21.004

Guan, M., Zhu, Y., and Zhang, Q. (2003). "Research on FSP of *Dendrocalamus membranaceus* according to its shrinkage," *Journal of Bamboo Research* (03), 40-43+54. DOI: 10.3969/j.issn.1000-6567.2003.03.009

Huang, M., Zhang, X., Yu, W., Li, W., Liu, X., and Zhang, W. (2016). "Mechanical properties and structural characterization of bamboo softened by high-temperature steam," *Journal of Forestry Engineering* 4, 64-68. DOI: 10.13360/j.issn.2096-1359.2016.04.010

Li, J., Sun, Z., and Xu, M. (2013). "Evaluation and grading of bending properties of moso bamboo strips near the bamboo green," *Forestry Machinery & Woodworking Equipment* 41, 47-49+54. DOI: 10.3969/j.issn.2095-2953.2013.08.014

Li, Y., and Lou, Z. (2021). "Progress of bamboo flatten technology research," *Journal of Forestry Engineering* 6, 14-23. DOI: 10.13360/j.issn.2096-1359.202012021

Li, Y., Lou, Z., Jiang, Y., Wang, X., Yuan, T., and Yang, F. (2020). "Flattening technique without nicked in curved bamboo strips," *Forestry Machinery & Woodworking Equipment* 48(05), 28-30, 34. DOI: 10.13279/j.cnki.fmwe.2020.0053

Li, Y., and Lou, Z. C. (2021). "Progress of bamboo flatten technology research," *Journal of Forestry Engineering* 6(04), 14-23. DOI: 10.13360/j.issn.2096-1359.202012021

Li, Y., Xu, B., Zhang, Q., and Jiang, S. (2016). "Present situation and the countermeasure analysis of bamboo timber processing industry in China," *Journal of Forestry Engineering* 1, 2-7. DOI: 10.13360/j.issn.2096-1359.2016.01.001

Li, Z., Liu, L., Ma, Y., Luan, Y., Liu, Y., Fei, B., Hu, J., Li, T., and Fang, C. (2022). "Effects of superheated steam treatment on the cupping and color of flattened bamboo boards," *Journal of Central South University of Forestry & Technology* 42(10), 168-176. DOI: 10.14067/j.cnki.1673-923x.2022.10.019

Liao, Z., and Jin, X. (1995). "The impact of stacking method on stacking strength," *Journal of Zhuzhou Engineering Institute* (01), 35-44.

Lin, H., Liu, H. Z., and Li, Y. J. (2015). "Bamboo material unfolding method," Zhejiang: CN104972540A, 14 October.

Liu, M. (2016). *Study on Superheated Steam and Vacuum Drying Technology of Bamboo Shoots*, Fujian Agriculture and Forestry University, Fujian, ON, China. DOI: 10.27018/d.cnki.gfjnu.2016.000064

Liu, Y. (2009). *Study on Poplar Drying Characteristic under Vacuum Superheat Steam,* Beijing Forestry University, Beijing, ON, China.

Liu, Y. (2021). "Study on the effect of moisture content on bamboo fiber opening," *China Southern Agricultural Machinery* 52(07), 92-94.

Lou, Z., Wang, Q., Sun, W., Zhao, Y., Wang, X., Liu, X., and Li, Y. (2021). "Bamboo flattening technique: A literature and patent review," *European Journal of Wood and Wood Products* 79, 1035-1048. DOI: 10.1007/s00107-021-01722-1

Lou, Z., Wang, X., Li, Y., Yang, F., and Zhao, Y. (2022). "Production technology of flattened bamboo flooring with bamboo outer layer," *China Forest Products Industry* 59, 49-52. DOI: 10.19531/j.issn1001-5299.202201008

Lu, Z., Shen, L., and Chen, X. (2007). "Effect of surface roughness of veneer overlaid panel on quality of water-borne sealer coating," *Chinese Journal of Wood Science and Technology* 2007(3), 42-44. DOI: 10.19455/j.mcgy.2007.03.014

Pan, H. (2018). *Research on Equipment of Removing Internodal Culm Wall and Inner Layer of Whole Bamboo,* Nanjing Forestry University, Nanjing, ON, China. DOI: 10.19531/j.issn1001-5299.202201008

Qin, W., Yu, H., Xu, M., Zhuang, X., Wang, H., Yin, M., Pan, X., and Liang, Y. (2024). "Effects of microwave softening treatment on dynamic mechanical and chemical properties of bamboo," *Journal of Materials Science* 59, 3488-3503. DOI: 10.1007/S10853-024-09391-0

Ren, X., Tang, J., Yu, C., and He, J. (2018). "Advances in research on the ecological effects of microplastic pollution on soil ecosystems," *Journal of Agro-Environment Science* 37, 1045-1058. DOI: 10.11654/jaes.2017-1409

Ribeiro, R. A. S., Ribeiro, M. G. S., and Miranda, I. P. A. (2017). "Bending strength and nondestructive evaluation of structural bamboo," *Construction & Building Materials* 146, 38-42. DOI: 10.1016/j.conbuildmat.2017.04.074

Rijckaert, V., Stevens, M., Vanacker, J., Meijer, M., and Militz, H. (2001). "Quantitative assessment of the penetration of water-borne and solvent borne wood coating in Scots pine sapwood," *Holz als Roh- und Werkstoff* 59(4), 278-287. DOI: 10.1007/s001070100208

Su, H., Liu, M., Liu, B., Yao, Y., and Fang, T. (2020). "Optimization of superheated steam combined vacuum drying technology of bamboo shoots by response surface method," *Science and Technology of Food Industry* 41(05), 182-187. DOI: 10.13386/j.issn1002-0306.2020.05.030

Varga, J., Demko, M., Kaščák, Ľ., Ižol, P., Vrabeľ, M., and Brindza, J. (2024). "Influence of tool inclination and effective cutting speed on roughness parameters of machined shaped surfaces," *Machines* 12(5), article 318. DOI: 10.3390/machines12050318

Wang, Q., Wu, X., and Yuan, C. (2020a). "Effect of saturated steam heat treatment on physical and chemical properties of bamboo," *Molecules* 25(8), article 1999. DOI: 10.3390/molecules25081999

Wang, X., Cheng, D., and Huang, X. (2020b). "Effect of high-temperature saturated steam treatment on the physical, chemical, and mechanical properties of moso bamboo," *Journal of Wood Science* 66, article 52. DOI: 10.1186/s10086-020-01899-8

Xie, Y., Zhuang, Y., and Hu, Y. (2024). "Study on the docking mechanism of market supply and demand to accelerate the development of 'using bamboo as a substitute for plastic' green industry," *Energy Conservation & Environmental Protection* (01), 6-14.

Xu, J., Liu, R., Wu, H., Qiu, H., Yu, Y., and Long, L. (2019a). "Coating performance of water-based polyurethane-acrylate coating on bamboo/bamboo scrimber substrates," *Advances in Polymer Technology* 2019, 1-8. DOI: 10.1155/2019/4264701

Xu, J., Liu, R., Wu, H., Qiu, H., Yu, Y., Long, L., and Ni, Y. (2019b). "A comparison of the performance of two kinds of waterborne coatings on bamboo and bamboo scrimber," *Coatings* 9, article 161. DOI: 10.3390/coatings9030161

Xu, Y., Zhang, Z., Chen, X., Wei, J., and Yu, W. (2024). "Study on the surface film adhesion of high-density bamboo scrimbers," *China Forest Products Industry* (02), 13-17+42. DOI: 10.19531/j.issn1001-5299.202402003

Yang, Y., Li, L., and Wu, L. (2008). "Effects of physical properties of moso bamboo on planning surface," *Journal of Beijing Forestry University* 30(1), 133-136. DOI: 10.3321/j.issn:1000-1522.2008.01.024

Yu, W., Ying, W., Zhong, J., and Zhang, W. (2021). "Equilibrium moisture content and dimensional stability of flattened bamboo softened by high temperature saturated steam," *Journal of Bamboo Research* 40(01), 27-31. DOI: 10.16521/jbr.2021.40.01.27

Zhang, X., Liu, H., Zhang, F., Jiang, Y., and Fei, B. (2021). "Analysis on the key technology of longitudinal, without grooves, integrated bamboo flattening," *China Forest Products Industry* 58(2), 43-47. DOI: 10.19531/j.issn1001-5299.202102010.

Zhang, Y., Yu, Y., and Yu, W. (2013). "Effect of thermal treatment on the physical and mechanical properties of *Phyllostachys pubescens* bamboo," *European Journal of*

Wood Products 71, 61-67. DOI: 10.1007/s00107-012-0643-6

Zhou, J., Feng, Y., and Liu, L. (2003). "Chemical constituents of the outer and the inner of bamboo, and its comprehensive utilization," *Biomass Chemical Engineering* (02), 8-10. DOI: 10.3969/j.issn.1673-5854.2003.02.002

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APPENDIX

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