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Study on the Effect of Flattening Modification on Bamboo Cutting Board and Corresponding Carbon Footprint Evaluation

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Abstract: Bamboo, as a renewable biomass material, has received wide public attention. However, due to the thin-walled and hollow structure of bamboo, the mainstream processing method is complex and requires splitting the bamboo into narrow strips and then gluing them together for further manufacturing products. In addition, the surface glue residue makes the safety of indoor applications a concern, especially for cutting boards that come into contact with food. In response to the above problems, this paper introduces a bamboo flattening technology, which can flatten and unfold the pre-treated bamboo into a large-size flattened bamboo board (FBB). The results show that, compared to untreated bamboo, the dimensional stability of the FBB was improved and the flexural strength and elastic modulus of the FBB were increased by about 8.0%. The flattened bamboo cutting board was manufactured with the FBB as the surface layer and had a moisture content and hardness value of 9.2% and 5080 N, respectively, and the accumulated dip peel length of any glue layer was less than 25 mm. The flattened bamboo cutting board is proved to be a carbon-neutral product with a carbon footprint value of −42.92 kg CO_2/t. This work provides a theoretical basis for the fabrication of large-size unspliced bamboo boards and provides new ideas for the scenario-specific application of FBBs. Using a FBB to make cutting boards can avoid contact between food and adhesives, making them more hygienic. The findings of this research can be used to make bamboo cutting boards more hygienic, environmentally friendly and possess excellent physical and mechanical properties.

Keywords: bamboo; cutting board; flattening; morphology; mechanical property; carbon footprint; saturated steam softening

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1. Introduction

Over the past century, the explosion of the world's population and the massive use of fossil fuels have led to the emission of large amounts of greenhouse gases into the atmosphere, resulting in global warming [1,2]. The aggravation of this climate problem has triggered a series of crises such as rising sea levels, a sharp decline in biodiversity, and a decrease in food production [3–5]. As a result, the gradual mitigation and solution of global warming has become the focus of attention of the whole society [6,7]. In recent years, biomass materials represented by wood have been widely used in the fields of construction materials, furniture and daily necessities because of their renewability and good carbon sequestration properties [8,9]. The superior physical and mechanical qualities, natural texture and the good processability of wood also meet the criteria for raw materials in such fields. The high demand for timber, however, is at odds with the slow growth rate of trees. The maintenance of the world's overall forest area is also seriously threatened by the lacking supply of wood, which will ultimately affect the global forest absorption and sequestration of greenhouse gases [10]. As another typical biomass material, the rapid growth rate and excellent physical and mechanical properties of bamboo make it a potential alternative to wood [11,12]. Focusing on the development of high-quality bamboo-based products helps to alleviate the problem of insufficient wood supply. At the same time, timely harvesting and processing of age-appropriate bamboo into bamboo-based products also stops the natural decay of bamboo in a short period of time and extends the carbon sequestration cycle of bamboo. Based on the above outstanding advantages of bamboo, bamboo has attracted attention in many fields. Bamboo has a long history of being used as a construction and structural material in various cultures around the world, especially in Asia and Latin America. Some of the applications of bamboo in construction include bridges, houses, buildings, scaffolding, fencing, and furniture [13]. Bamboo has gained more attention in recent years as a potential alternative to conventional materials, due to its aesthetic appeal, low cost and environmental benefits [14].

Unfortunately, bamboo processing is restricted by its characteristics of having a hollow structure and thin wall [15]. The current mainstream processing method is mainly to split the bamboo tube into bamboo slices or bundles, and then reorganize and glue them into laminated bamboo timber or bamboo scrimber [16–19]. In addition, there are some new bamboo processing methods that have emerged in recent years. Chen et al. [20,21] created a bamboo winding pipe by encasing helically wound layers of thin but strong bamboo sliver curtains in a protective matrix of gauze wrap, thermosetting resin and powdered bio-filler. Huang et al. [22,23] manufactured arc-shaped bamboo laminated lumber by assembling equal-arc-shaped bamboo splits in the same arc direction and then gluing them directly. These new technologies are widely used in the field of structural materials. Compared to wood, which can be obtained in large sizes simply by sawing directly, bamboo is more complex to process, and the final bamboo lumber inevitably has splices, thus limiting the application of bamboo in some scenarios [24,25]. Typically, in the cutting board sector, wood has been the main base material due to its suitable hardness and good antibacterial properties, while bamboo has struggled to outperform wood despite similar performance [26]. This is mainly due to the fact that bamboo cutting boards made from laminated bamboo timber have a series of problems compared to wooden cutting boards: (1) the glue line at the splicing of the cutting board surface is in direct contact with food, which is a food safety hazard; (2) as the base material of the cutting board, the laminated bamboo timber needs to be spliced and glued together to manufacture, and the adhesive content is high, which leads to higher formaldehyde emission from the cutting board and has a certain negative impact on the indoor environment; (3) in the course of prolonged use, the cutting board is vulnerable to fracture due to weak splices on the surface of the cutting board [27]; (4) the production process of bamboo laminated timber has a large amount of planing and low material utilization, which is not conducive to the environmental friendliness of the cutting board.

Thus, a novel method in bamboo processing is urgently needed to make large-size bamboo lumbers without splicing and overcome the drawbacks of bamboo-based materials in some particular application scenarios. In this context, the bamboo flattening modification technology was developed [28–30]. This technology softens the bamboo tube by means of high temperature, saturated steam or microwave, and then uses rollers to flatten the entire tube with curvature into a large-size flattened bamboo board (FBB). The whole process no longer requires splicing and gluing [31–33]. By the flattening modification, the morphology of bamboo is changed, and the physical and mechanical properties could be improved, which will be more suitable for the requirements of the substrate for cutting boards [34,35]. In addition, the absence of adhesives on the surface of the FBB can avoid food safety risks in the use of cutting boards and reduce the negative impact on the indoor environment. The whole process of bamboo flattening is also different from the traditional bamboo processing, and its processing method could be further simplified, which is expected to further reduce the carbon emission of the processing [36]. The use of a FBB as a base material for bamboo cutting boards is anticipated to solve the problems faced by bamboo cutting boards nowadays. In addition, not only for cutting boards but also for other applications with higher requirements for substrate size, physical and mechanical properties, appearance and safety, such as flooring, furniture, building materials and decorative materials, the FBB will have greater potential. It is necessary to analyze the effect of bamboo flattening modification technology applied to specific products.

In view of the potential advantages of bamboo flattening modification, we manufactured flattened bamboo cutting boards (FBCBs) using the modified FBB. This work compared the changes in morphological characteristics and physical and mechanical properties of bamboo before and after the flattening modification and discussed the performance enhancement and mechanism of the flattening modification on bamboo materials. In addition, the physical and mechanical properties of the FBCBs were tested and compared with the required performance criteria for cutting boards, and the advantages of flattening modification technology applied to cutting boards were discussed. Finally, the carbon footprint of FBCBs was evaluated to analyze their environmental friendliness. The assessment of the effect of flattening modification on bamboo cutting boards in this work demonstrated the contribution of flattening modification on bamboo material in a more specific way.

2. Materials and Methods

2.1. Raw Materials

Four-year-old fresh moso bamboo (*Phyllostachy heterocycla*) was harvested in Gao'an City, Jiangxi Province. Bamboo culms with a wall thickness of 8 mm and an outer diameter of 100 $\pm$ 5 mm were selected from the same batch. The initial moisture content of moso bamboo was approximately 70%−80%. Urea-formaldehyde resin was obtained from Hangzhou Zhuangyi Furniture Co., Ltd., Hangzhou, China. The solid content of the UF resin adhesive was 40%−50%, the viscosity was 40–80 mPa·s and the pH was 7–8.

2.2. Bamboo Flattening Modification

Before flattening modification, bamboo should be pretreated with truncation, inner nodes removal, outer layer removal and grooving. The modification of bamboo to a flattened bamboo board (FBB) mainly involves two processes: softening and flattening. First, the grooved bamboo tubes were subjected to saturated steam softening treatment at 175 °C for 5 min in a sealed pressurized tank (12R3426-1, Hangzhou Rongda Boiler Container, Hangzhou, China). Then, flattening was carried out immediately before the temperature of the bamboo dropped. Finally, the bamboo tubes were flattened into FBBs after passing through a pair of cylindrical rollers in the vertical direction, among which, the roller facing the inner surface of the bamboo tube has engraving knives on its surface, and the other roller has a smooth surface. The engraving knives on the roller present a sharp conical shape with a depth of 4–5 mm, evenly distributed on the roller, and the distance between two adjacent engraving knives is about 4 mm. The compression force exerted on the bamboo was about 1–2 MPa, and the speed of the rollers was 60–80 r/min. After flattening, the bamboo maintained a high moisture content and remained basically the same as the initial moisture content, approximately 70%−80%. As a result, the bamboo needs to be dried for a period of 5–7 days at a controlled temperature of 35–60 °C, ending when the moisture content of the bamboo boards reaches less than 9%. The final size of the FB was 500 mm in length, 300 mm in width and 8 mm in thickness.

2.3. Manufacturing of Flattened Bamboo Cutting Board (FBCB)

FBCBs were manufactured in Hangzhou Zhuangyi Furniture Co., Ltd. The FBCB was based on a three-layer structure. The upper and lower outer layers were FBBs, and the core layer was a single-layer bamboo laminate lumber composed of bamboo strips. The production process of the FBCB was composed of several main processes including the gluing of FBBs and bamboo laminated lumbers, assembly and hot pressing, and the post-processing of the chopping boards. The adhesive selected was urea-formaldehyde resin adhesive. The coated area was 200 g/m^2 for a single glue line, and the automatic coater was used to apply the adhesive through the way of a rolling coating with a speed of 15 m/min. The hot-pressing temperature was 95~100 °C, the pressure was 3 MPa and the time was 20 min. The final size of the FBCB was 400 mm (length) × 280 mm (width) × 22 mm (thickness).

2.4. Characterization

The morphology characteristics of untreated bamboo and FBB samples were investigated by SEM (Quanta 200, FEI Company, USA). The density, shrinkage, compressive strength parallel to the grain, tensile strength parallel to the grain, modulus of rupture (MOR) and modulus of elastic (MOE) of untreated bamboo and FB samples were determined according to Standard GB/T15780-1995 (China). The specimen size for the density test was 10 × 10 × t mm (length × width × thickness), and the air-dry and oven-dry densities were obtained by measuring the size and mass of the specimens in air-dry and oven-dry states and calculating the mass-to-volume ratio. The dry shrinkage rate was tested using saturated moisture specimens with dimensions of 10 × 10 × t mm (length × width × thickness). The dimensions of air-dried and oven-dried specimens were measured separately and compared with the initial specimens to calculate the shrinkage rate of the dimensions. The compression strength parallel to the grain, tensile strength parallel to the grain, MOR and MOE were tested by a universal mechanical testing machine. The specimen sizes were 20 × 20 × t mm, 280 × 10 × t mm and 160 × 10 × t mm (length × width × thickness), respectively. Among them, the specimens of tensile strength were bone shaped. Each test was repeated 15 times. The moisture content, working surface hardness and dipping peeling length of the FBCB samples were determined according to Standard GB/T 38742-2020 (China). The working surface hardness of the FBCB was tested by electric contact hardness testing equipment. The size of the specimens was 70 × 50 × t mm (length × width × thickness), and the moisture content of the specimens was controlled at 12%. The specimens with the size of 50 × 50 × t mm (length × width × thickness) were made and tested for moisture content. After weighing the mass, specimens were dried in the oven (temperature 103 ± 2 °C) until the mass was constant. The moisture content is the ratio of the mass difference to the oven-dried mass. The MOR of the FBCB was tested by a universal mechanical testing machine and the size of the specimens was (10 t + 50) × 50 × t mm (length × width × thickness). The size of the dipping peeling length test specimen was 75 × 75 × t mm (length × width × thickness). After dipping for 3 h in hot water at 63 ± 3 °C, the specimens were taken out and dried in the oven at 63 ± 3 °C for 3 h to measure the peeling length. Each test was repeated 6 times. The formaldehyde emission of the FBCB samples was determined according to Standard GB/T 18580-2017 (China). The formaldehyde emission was measured by the 1 m^3 climate chamber method, with a surface area of 1 m^2 of the specimens, which were put into the 1 m^3 climate chamber for testing after equilibrating the moisture content. The results of the measured data were analyzed and the normality of the data distribution and homogeneity of variances were checked. A *t*-test was conducted to determine the significance between the samples.

2.5. Carbon Footprint Assessment

By deducting the carbon storage of the FBCB from the total carbon emissions, the carbon footprint was calculated. The transportation, production process and raw materials are the main sources of carbon emissions. A reduced carbon footprint is a direct result of the associated environmental advantage.

2.5.1. Carbon Storage of FBCB

Since the resin content in the FBCB is low, the mass of the FBCB is mainly derived from bamboo. Thus, the oven-dry mass in the product (B_{odw}) is calculated as below:

$$B_{odw} = B_w - (B_w \times W) \quad (1)$$

where, W and B_w are the moisture content and the mass of the product, respectively. The mass of carbon in the product (m_C) is calculated according to Equation (2):

$$m_C = B_{odw} \times f_c \tag{2}$$

where f_c is the corresponding mass fraction, which is supposed to be 50% [37]. Accordingly, the mass of CO_2 fixed in the product (m_{CO_2eq}) can be determined as below:

$$m_{CO_2eq} = m_C / \left(Ar_C / Ar_{CO_2} \right) \tag{3}$$

where Ar_C and Ar_{CO_2} are the relative molecular mass of C and CO_2. The carbon storage effect (C_b) is calculated according to the British Standards Institute PAS 2050:2008, as described in Equations (4) and (5):

$$C_b = m_{CO_2eq} \times k \tag{4}$$

$$k = \begin{cases} 0.76 \times t_0/100, 2 < t_0 \leq 25 \\ t_0/100, 25 < t_0 < 100 \end{cases} \tag{5}$$

where k is the mass factor for carbon storage, t_0 is the number of years for which the product has a full carbon storage effect; the service life t_0 of FBCB is supposed to be 30 years.

2.5.2. Carbon Emissions of FBCB

The mass of raw materials for the products (B_R) is calculated as below:

$$B_R = P_w / p_B \tag{6}$$

where P_w is the mass of the product and p_B is the utilization ratio of raw materials. The utilization ratio of the FBB is calculated according to the corresponding yield. As the mass loss of raw materials is inevitable due to the sawing, sanding and other treatments during production, the utilization ratio of raw materials is calculated at 90% [38].

The CO_2 emission equivalent (C) for raw materials (C_e) is converted as below:

$$C_e = m_p \times f_m \tag{7}$$

where m_p is the mass of the raw material, and f_m is the carbon emission factor (f) of the raw material, which can be obtained from the IPCC database [39]). The CO_2 emission equivalent for electricity consumption (C_t) is calculated according to Equation (8):

$$C_t = W_E \times f_t \tag{8}$$

where W_E is the electrical energy consumption, which is calculated by multiplying the equipment power and corresponding usage time. The relevant data came from the nameplates of the corresponding equipment or actual detection. f_t is the carbon emission factor of electricity consumption, which is 0.801 kg CO_2/kWh according to the local power grid. The proportion of CO_2 emission (P_C) is calculated according to Equation (9):

$$P_C = C / \sum C_i \times 100\% \tag{9}$$

where C is the corresponding CO_2 emission equivalent of a given process and C_i is the CO_2 emission equivalent of each process.

2.5.3. Carbon Footprint (C_p) Estimation of FBCB

The C_p value of the FBCB was calculated by subtracting the carbon storage effect contributed by the products from the CO_2 emission equivalent generated in the whole process, as described in the following Equation (10):

$$C_p = \sum C - \sum C_b \tag{10}$$

The flowchart of the research method is shown in Figure 1.

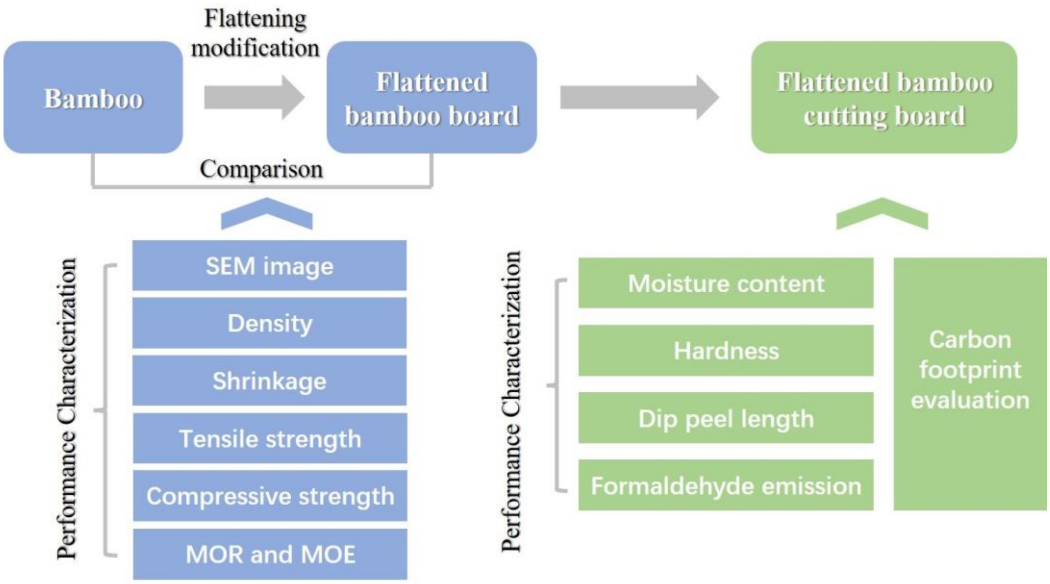

Figure 1. Flowchart of the research method.

3. Results and Discussion

3.1. Effect of Flattening Modification on Bamboo Morphology

Figure 2 shows the process of bamboo flattening modification and the morphological characteristics of bamboo before and after flattening. As shown in Figure 2a, the grooved bamboo tube with the green and yellow surfaces removed was first softened by high-temperature saturated steam treatment and the groove was widened. Through flattening rollers, the curved bamboo tube was flattened into a FBB (Figure 2b). Figure 2c illustrates the inner surface morphology of the FBB at the macroscopic scale. In order to achieve the effect of stress relief, the flattening roller on the side of the bamboo inner surface was equipped with engraving knives, and the marks left by the knives can be clearly observed on one of the FBB surfaces (the inner surface of the bamboo tube after flattening). After flattening modification, the FBB can obtain a large format up to 500 mm in length and 300 mm in width. This dimensional feature distinguishes the FBB from conventional bamboo basic materials such as bamboo strips and bamboo bundles. The SEM images of untreated bamboo are presented in Figure 3a–c. The cell lumen of parenchymal cells and vessel cells were clearly visible. Compared with the untreated bamboo, the parenchymal cells and vessel cells of the FBB underwent significant deformation, being compressed from round to oval (Figure 3d–f), which increases the degree of densification of the FBB. The biggest effect of flattening modification on bamboo morphology is to unfold bamboo tubes with curvature directly into large-size FBBs without gluing and splicing.

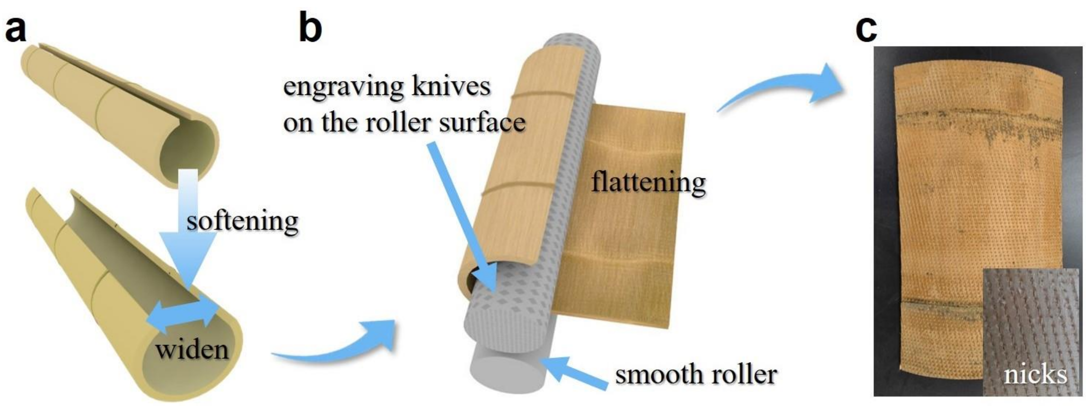

Figure 2. Schematic diagrams of (**a**) bamboo softening and (**b**) flattening; (**c**) the physical picture of the FBB inner surface and the enlarged view in the lower-right corner.

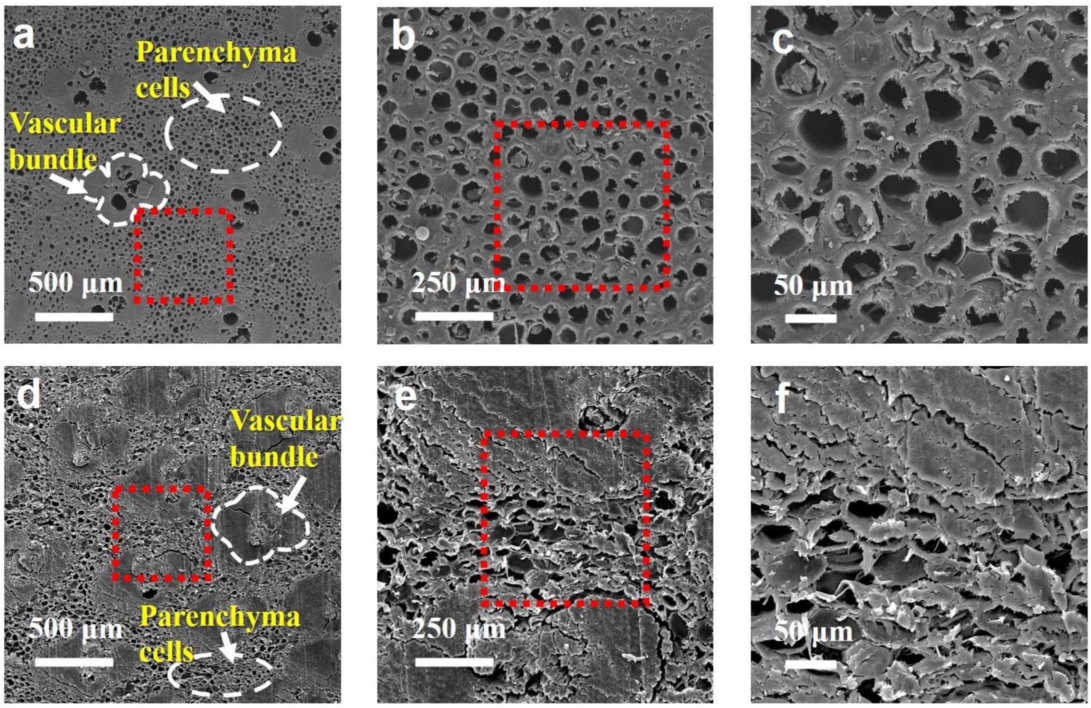

Figure 3. SEM images of (**a**–**c**) untreated bamboo and (**d**–**f**) FBB.

3.2. Comparison of Physical and Mechanical Properties of Bamboo before and after Flattening Modification

The physical properties of bamboo before and after flattening modification are shown in Figure 4. After flattening modification, the air-dry and oven-dry densities of the FBB were 0.70 and 0.66 g/cm^3, respectively, which were slightly lower compared to 0.72 and 0.70 g/cm^3 for untreated bamboo (Figure 4a,b). This is mainly attributed to the partial degradation of the main chemical components of the bamboo during the flattening modification process [34,40]. Despite the parenchyma cells and vasculature of the FBB clearly exhibiting compression in the SEM images (Figure 3), the notches and cracks created during the flattening modification increased the internal voids and ultimately decreased the density of the FBB in comparison to untreated bamboo. As shown in Figure 4c,d, the air-dry and oven-dry shrinkage of the FBB reduced compared with untreated bamboo. Among them, the chordwise shrinkage decreased by about 47%, which is more significant. This means that the dimensional stability of the FBB is enhanced after the flattening modification. This is mostly due to the fact that a significant proportion of hygroscopic hemicellulose was degraded and the number of free hydroxyl groups in the bamboo cell wall gradually decreased during the flattening modification [30,34].

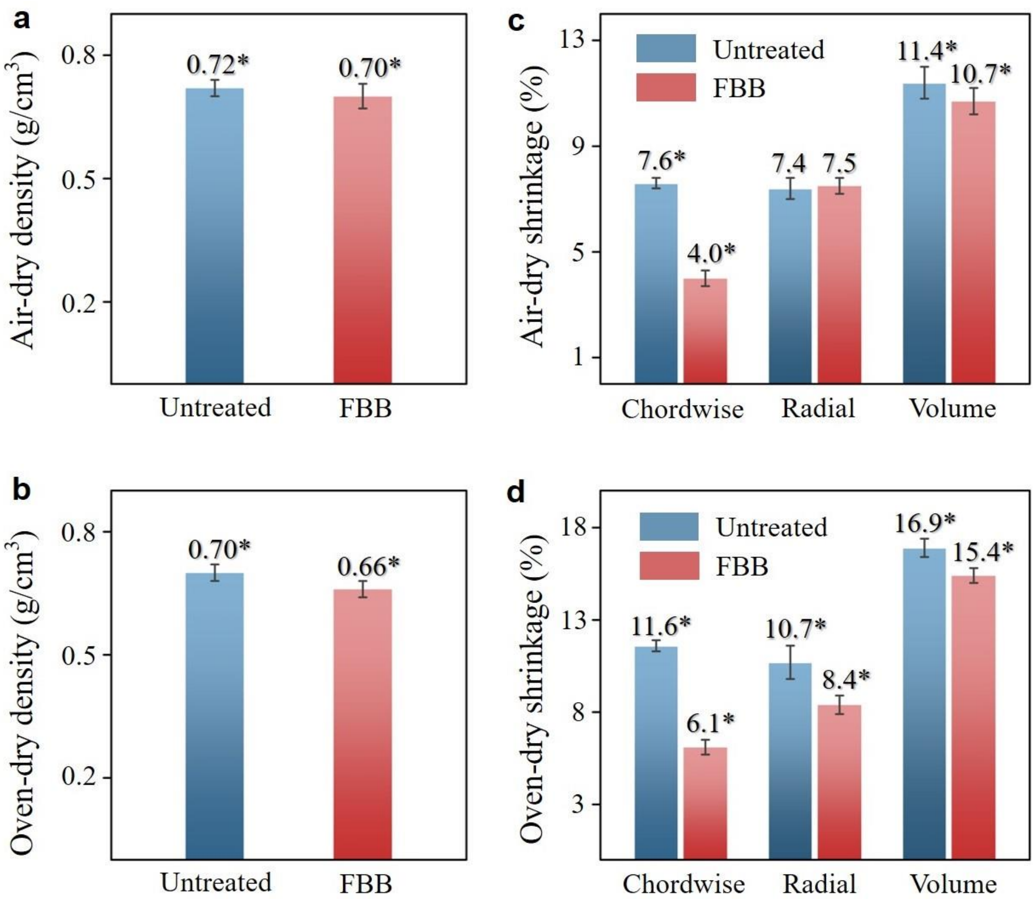

Figure 4. Comparison of (**a**) air-dry density, (**b**) oven-dry density, (**c**) air-dry shrinkage and (**d**) oven-dry shrinkage of bamboo before and after flattening modification. The data in the graph are average values and the error bars represent standard deviations. Values followed by "*" indicate that the *p*-value of the *t*-test is less than 0.05, and significant differences appear between untreated and FBB data, while unmarked values indicate no significant differences.

Figure 5 shows the mechanical properties of bamboo before and after flattening modification. Compared with untreated bamboo, the tensile strength of the FBB decreased by 38.5% (Figure 5a). The compression strengths of untreated bamboo and the FBB were 46.89 and 45.28 MPa, respectively, with a small difference (Figure 5b). This is mainly because the flattening rolls with engraving knives cut some of the fibers during the flattening modification (as shown in Figure 3). The bamboo fiber structure is more akin to a geometry that is purely tension resistant and offers reinforcement benefits that are more pronounced in tension as opposed to compression [41,42]. As a result, the tensile properties of the FBB are significantly and negatively impacted in the case of partial fiber destruction, whereas the compression properties are barely changed. The hemicellulose, which connects cellulose and lignin, diminished as a result of the flattening modification, weakening the resistance to the buckling of cell walls. The MOR and MOE of the FBB, however, increased by 7.9% and 8.0% compared with untreated bamboo. This is primarily due to the fact that the cell wall of parenchyma cells grew thinner and more deformable after flattening alteration (as shown in Figure 3c,f). Parenchymal cells can withstand greater strain and act as a buffer, delaying bamboo failure and improving its flexural ductility. After saturated steam softening, the relative crystallinity of the fiber increased and the surface of the fiber became smoother [32,33]. When compared to untreated bamboo, the FBB had better bending properties due to its improved fiber properties, which increased its capacity to withstand deformation. After flattening modification, the FBB achieves the unique advantage of a large size and no splicing while maintaining the excellent physical and mechanical properties of bamboo, which provides a solid foundation for the development of the FBCB and ensures the high quality of the FBCB.

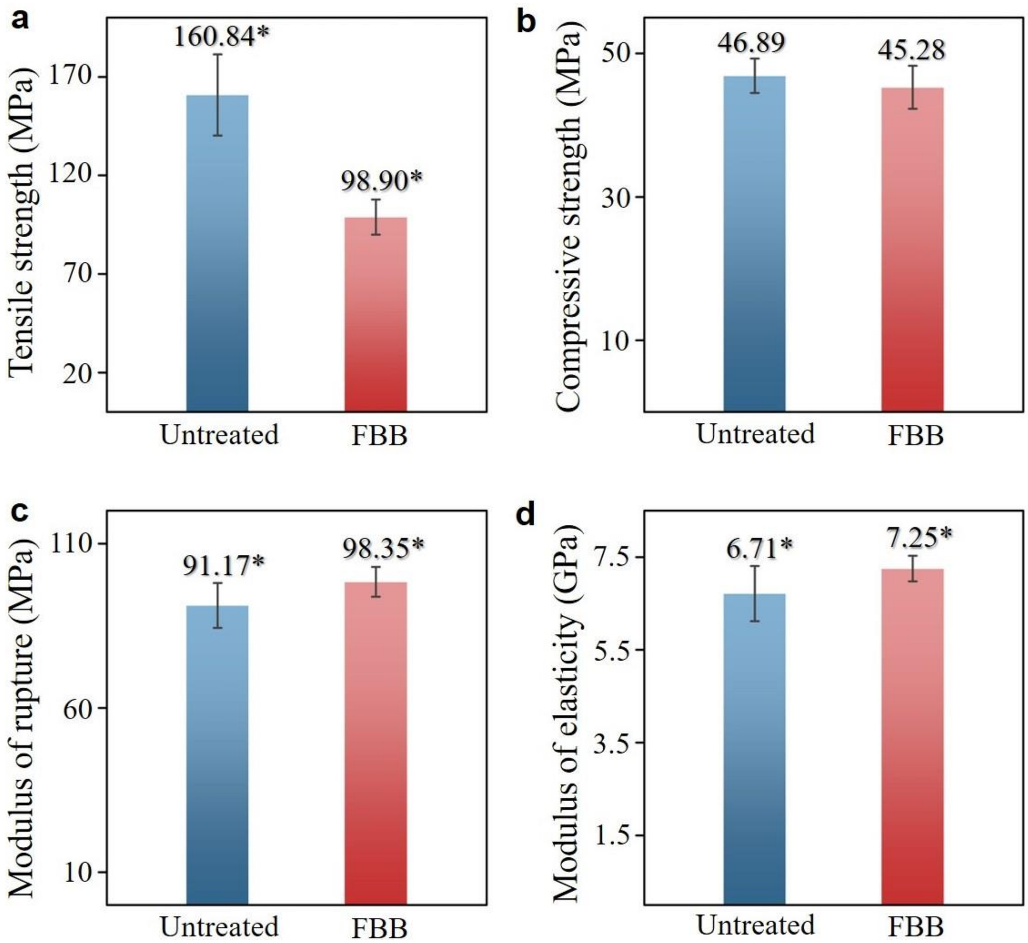

Figure 5. Comparison of (**a**) tensile strength parallel to the grain, (**b**) compressive strength parallel to the grain, (**c**) modulus of rupture and (**d**) modulus of elasticity of bamboo before and after flattening modification. The data in the graph are average values and the error bars represent standard deviations. Values followed by "*" indicate that the *p*-value of the *t*-test is less than 0.05, and significant differences appear between untreated and FBB data, while unmarked values indicate no significant differences.

3.3. Fabrication and Physical and Mechanical Properties Analysis of FBCB

As shown in Figure 6a, a traditional bamboo cutting board is made of bamboo strips bonded together. The staggered bamboo nodes show the arrangement of the bamboo strips. In addition, the glue lines left by the bonding are clearly visible on the surface of the cutting board. This means that the adhesive can come into direct contact with the food placed on the surface of the cutting board during the use phase, which poses a series of food safety hazards. In addition, the multiple interfaces created due to bonding make the cutting board have more weak points, increasing the risk of cracking. Figure 6b illustrates the fabrication process of the FBCB. The FBCB differs from traditional bamboo cutting boards in that the upper and lower layers are whole FBBs, while the middle layer is a laminated lumber composed of bamboo strips. As a whole, the layers of the FBCB are cross-laminated in the direction of the fiber grain, which is helpful for dimensional stability. As shown in Figure 6c, since the outer layer of the FBCB is the whole-piece FBB, the FBCB has a smooth surface and no glue lines. This can prevent the adhesive from contaminating food and reduce formaldehyde emission to guarantee the safety of the usage process. Additionally, the splice-free surface ensures the stability of the overall mechanical properties of the cutting board, and the complete bamboo node texture adds to the aesthetic appeal of the FBCB.

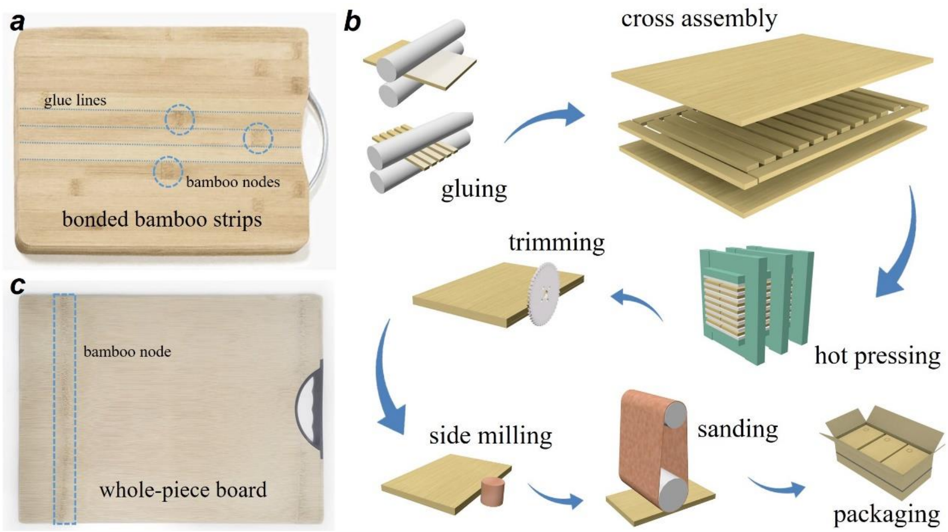

Figure 6. (**a**) Presentative picture of the laminated bamboo chopping board; (**b**) schematic of the production process of FBCB; (**c**) presentative picture of FBCB.

Table 1 lists the physical and mechanical properties of the FBCB. The moisture content of the FBCB was 9.2%, the hardness value of the FBCB reached 5080 N and the maximum dip peel length of the FBCB was 25 mm. All the above physical and mechanical properties of the FBCB can meet the requirements of the relevant standards of bamboo cutting boards (GB/T15780-1995). The successful performance of the FBCB is also attributed to the outstanding performance of the FBB as a base material. The appropriate moisture content range of the FBCB avoids significant wet expansion and dry shrinkage when the ambient humidity changes. The large hardness of the FBCB ensures that the surface is not easy to leave knife marks on, avoiding bacterial growth that occurs because the knife marks are difficult to clean, thus ensuring food hygiene. The small dip peel length indicates the good adhesive layer solidity of the FBCB, which contributes to the stability of the three-layer structure and prevents cracking. Additionally, the formaldehyde emission of the FBCB was 0.2 mg/L and achieves the E0 level of Standard GB/T 18580-2017 (China), which ensures excellent security and environmental friendliness of the FBCB for applications in indoor scenarios.

Table 1. Physical and mechanical properties of FBCB.

Property	Standard Request	Test Result
Moisture content (%)	8.0~15.0	9.2
Hardness (N)	≥3100	5080
Dip peel length (mm)	≤25 (any bonding layer)	max: 25
Formaldehyde emission (mg/L)	E0: 0.5	0.2

3.4. Carbon Footprint Evaluation of FBCB

The carbon footprint is estimated by subtracting the carbon storage of the FBCB from the sum of carbon emissions. A reduced carbon footprint reflects the corresponding environmental benefits and a negative carbon footprint value indicates a net sequestration of CO_2. The CO_2 emission equivalent for the transportation process is calculated as 5.10 kg (Table 2). As the main raw material, bamboo is in high demand and accounts for the bulk of carbon emissions during transportation with a P_C value of 86.86%. The CO_2 emission equivalent for the raw materials used in manufacturing was estimated using Equation (7) and the results are shown in Table 3. The CO_2 emission equivalent from the raw materials for producing 1 t of FBCBs is 69.17 kg. The CO_2 emission equivalent for the production of FBCBs was estimated using Equation (8), as shown in Table 4. The processing procedure of FBCBs consists of three parts and the total CO_2 emission equivalent is 382.31 kg. Among all the processes, the CO_2 emission of hot pressing is the largest followed by two drying processes and the corresponding P_C values are 26.61%, 18.57% and 8.42%, respectively. This is mainly because hot pressing requires curing the adhesive at high temperatures while drying requires a continuous supply of certain temperatures and air circulation to drain the moisture from the bamboo over a longer period of time, and these processes produce higher carbon emissions. For transportation, additional materials and production combined, there are 456.58 kg of CO_2 emission equivalents. According to Equation (10), it is estimated that 1 t of FBCBs with a service life of 30 years can fix about 1.7 t CO_2 in the form of organic matter. The carbon storage effect is 499.5 kg and the carbon footprint is −42.92 kg CO_2. Since the carbon footprint of FB-based glulam is negative, it could be considered that the FBCB is an environmentally friendly carbon-neutral product.

Table 2. CO_2 emissions for transportation in producing 1 t of FBCBs.

Transported Material	Fuel	Fuel cnsm. ($L\ t^{-1}\ km^{-1}$)	Dist. (km)	Weight (t)	f of Fuel ($kg\ L^{-1}$)	C (kg)	P_C (%)
Bamboo	Diesel	0.015	50	2.27	2.6	4.43	86.86
Carton	Gasoline	0.020	20	0.03	2.3	0.03	0.59
Adhesive	Gasoline	0.020	200	0.07	2.3	0.64	12.55
Total						5.10	100

Table 3. CO_2 emissions for the raw materials in producing 1 t of FBCBs.

Raw Material	f ($kg\ kg^{-1}$)	Weight (t)	C (kg)	P_C (%)
Carton	0.90	0.03	28.80	41.64
Adhesive	0.60	0.07	40.37	58.36
Total			69.17	100

Table 4. CO_2 emissions for the production of 1 t of FBCBs.

Part	Process	Power (kw)	Time (h)	Power cnsm. (kWh)	C (kg)	P_C (%)
Bamboo flattening	Truncation	15.40	0.64	9.80	7.85	2.05
	Inner nodes removal	6.75	1.14	7.69	6.16	1.61
	Outer layer removal	11.05	0.51	5.64	4.52	1.18
	Grooving	8.50	1.18	10.06	8.06	2.11
	Softening	10.00	2.66	26.64	21.34	5.58
	Flattening	9.70	1.08	10.48	8.39	2.19
	Cooling and shaping	2.20	2.95	6.50	5.20	1.36
	Drying	6.00	14.77	88.62	70.99	18.57
	Thickness planing	18.00	2.13	38.36	30.73	8.04
Bamboo strips fabricating	Truncation	15.40	0.32	4.90	3.93	1.03
	Slitting	31.50	0.28	8.97	7.19	1.88
	Rough planing	39.50	0.71	28.21	22.59	5.91
	Carbonizing	22.00	0.96	21.08	16.89	4.42
	Drying	6.00	6.70	40.20	32.20	8.42
	Fine planing	28.50	0.60	17.08	13.68	3.58

Table 4. *Cont.*

Part	Process	Power (kw)	Time (h)	Power cnsm. (kWh)	C (kg)	P_C (%)
FBCB fabricating	Gluing	2.20	0.47	1.03	0.83	0.22
	Assembly	1.50	0.28	0.42	0.34	0.09
	Hot pressing	95.50	1.33	127.02	101.74	26.61
	Trimming	8.75	1.05	9.19	7.36	1.93
	Side milling	6.00	0.40	2.40	1.92	0.50
	Sanding	28.57	0.45	12.86	10.30	2.69
	Packaging	0.75	0.17	0.13	0.10	0.03
Total				477.28	382.31	100

4. Conclusions

In this work, bamboo was made into a FBB by the flattening modification technique, and further, a FBCB with a FBB as the upper and lower surface was manufactured. The SEM images showed that the parenchymal cells and vessel cells of the FBB underwent significant deformation after flattening modification. Compared to untreated bamboo, the dimensional stability of the FBB was improved and the density was decreased slightly. Although the tensile properties parallel to the grain of the FBB decreased after the flattening modification, the value still reached 98.9 MPa, while the compressive properties of the FBB did not change much before and after the modification. The difference is that following the flattening modification, the flexural strength and elastic modulus of the FBB rose by about 8.0%. The FBCB had a moisture content and hardness value of 9.2% and 5080 N, respectively, and the accumulated dip peel length of any glue layer was less than 25 mm. The formaldehyde emission of the FBCB was 0.2 mg/L and achieved the E0 level of Standard GB/T 18580-2017 (China). The FBCB was proved to be a carbon-neutral product with a carbon footprint value of −42.92 kg CO_2/t. The manufacturing of large-size unspliced FBBs is made possible by the flattening modification technology, enhancing the application scenarios for bamboo. This research provides new ideas for the application of FBBs and supports the further development of FBBs. Using FBBs to make cutting boards can avoid contact between food and adhesives, making it more hygienic. The findings of this research can be used to make bamboo cutting boards more hygienic, environmentally friendly and with excellent physical and mechanical properties. The focus of the subsequent research can be on improving the manufacturing process of FBBs, exploring the mechanism of flattening modification technology and exploring the application of FBBs in other fields such as building structural materials.

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