Liu *et al. J Wood Sci* (2020) 66:14
https://doi.org/10.1186/s10086-020-01862-7

Journal of Wood Science

ORIGINAL ARTICLE Open Access

# Properties of common tropical hardwoods for fretboard of string instruments

Meihong Liu, Limin Peng, Shaoyi Lyu and Jianxiong Lyu*

**Abstract**

Fretboards of string instruments are usually made of rare woods that commonly have a high density, strength, and hardness; further, they are wear resistant, uniform in texture, and feature an elegant color. To reduce the consumption of scarce timber resources, especially of endangered tropical hardwood species, suitable replacement materials should be identified. The substitute can be either common tree species having similar characteristics, or fast-growing plantation wood that has undergone modifications to match the performance of precious woods. This study compares the anatomical structure, physical features, mechanical properties, and surface color of three precious woods traditionally used in fretboards (ebony, Indian rosewood, and African blackwood) against maple, which is used for the backboard, ribs, and necks of string instruments. Based on the data, a set of performance evaluation indices for selecting alternative materials for fretboards is proposed. In specific, the replacement wood should be a diffuse-porous tropical hardwood with few vessels and a smaller diameter, thick fibrous walls, and a cell wall rate of more than 50%. In terms of physical properties, it should have low swelling coefficients for moisture and water absorption, and dimensional stability. The replacement should also display hardness values greater than 9.0 kN in the cross-section and greater than 6.0 kN in the tangential and radial sections. Further, it should have a high modulus of rupture (> 149 MPa) and elasticity (> 14.08 GPa), good impact bending strength, and good wear resistance (80–150 mg/100 *r*). To satisfy the traditional aesthetics, the wood surface color should be black, dark brown, or dark purple-brown, with colorimetric parameters in the range of $0.0 < L^* < 30.0$, $0.0 < b^* < 6.0$, and an $a^*$ value as small as possible. The evaluation indicators used for searching potential high-quality alternative tree species are not the same as those for replacing traditional fretboard materials using modified fast-growing plantation wood. The physical and mechanical properties and the surface color of traditional precious fretboard wood are important evaluation indicators for whether the modified fast-growing plantation wood can replace the traditional fretboard wood.

**Keywords:** Tropical hardwoods, Fretboard, String instruments, Wood anatomy, Mechanical properties, Color parameters

## Introduction

The fretboard of traditional string instruments is mainly made of tropical hardwoods, such as ebony, Indian rosewood, African blackwood, and other precious woods that are characterized by a high density, high strength, and hardness, good wear resistance and dimensional stability, and a beautiful color [1, 2]. However, these trees have a long growth cycle, the yield is low, and the wood is easily damaged during production. In addition, Indian rosewood and African blackwood used for fretboard are included (in Appendix II of the CITES) [3], so these woods and their products are restricted in world trade [4, 5]. Ebony's long growth cycle, low yield, and vulnerability also limit its applications in musical instruments. Therefore, it is urgent to seek sustainable alternative woods with similar properties. Another option is improving the function of fast-growing plantation wood using physical, chemical, and biological treatments [6–9] to match the performance of precious wood.

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*Correspondence: jianxiong@caf.ac.cn
Research Institute of Wood Industry of Chinese Academy of Forestry, Hunan Collaborative Innovation Center for Effective Utilizing of Wood & Bamboo Resources, Beijing 100091, China

When musicians play string instruments, they adjust the pitch by pressing the strings to the fretboard. The fretboard is often marked by frets to determine the pitch positions [10]. The poor contact between the strings and the fretboard can affect the tone and pitch, such as noise and wolf sounds [11]. The rigid fretboard has better resistance to bending and torsional deformation caused by the tension of different strings and the compressive force of the strings and fingers [12]. Over time, the fretboard's surface can become abraded, leaving pits or grooves especially in the high-pitched parts. Moreover, the fretboard is glued to the neck and increases the overall stiffness of neck. The stiff fretboard can inhibit the reduction in the resonance frequency of the soundboard, making the instrument sound stronger and more uniform [13]. Thus, the wood used for fretboards should have good wear resistance, high hardness, and high stiffness while maintaining excellent flexibility.

The researchers have comprehensively examined the performance requirements and evaluation indices of soundboard wood. However, corresponding studies on the fretboard are still insufficient and unsystematic [14]. Paté et al. [15, 16] studied two guitars that only differ in the fretboard material (ebony or Indian rosewood). The well-known "dead spot" phenomenon was observed, where a frequency resonance of the string and the main structure at the coupling point lead to an abnormal damping of the note. The two guitars showed strikingly different behavior in the dead spots in terms of the affected notes as well as how much they were affected [17]. Through a comparative study of sound and driving-point conductance of these two guitars, it was observed that the fretboard wood had an influence on the location of and the susceptibility to dead spots. When a frequency resonance of the string and the main structure at the coupling point occurs, the string damping may be bigger for guitars with rosewood fretboards [18]. This indirectly proves that fretboard wood will affect the timbre of the string instrument. Hiziroglu et al. used ebony, Brazilian rosewood, and Indian rosewood in violin fretboards and compared the resultant tonal qualities. They found that the different woods led to different sound characteristics: the timbre was clear and harmonious for the ebony fretboard, while it was delicate and soft for the rosewood fretboard [19]. Sproßmann et al. studied the use of African blackwood (*Dalbergia melanoxylon* Roxb.) instead of ebony (*Diospyros crassiflora* Hiern.) in the fretboards of classical guitars, and that of ziricote to replace Indian rosewood in the soundboard. African blackwood was found to be similar or superior to ebony in terms of the physical, mechanical, and acoustic properties; and therefore, the former is more suitable for use in the fretboard [20]. In addition, African blackwood and ebony are so similar in color and texture that it is difficult to distinguish them. This is an important reason why African blackwood has been widely used in the market [1]. While Indian rosewood is also a popular choice for fretboards, Sproßmann et al. considered its performance only in the soundboard. In the previous experiments, it was found that the acoustic vibration performance of the fretboard wood is not an important factor, and the corresponding requirements are much lower than those for the soundboard wood.

This paper systematically analyzes the anatomical characteristics, physical and mechanical properties, and surface color of three commonly used fretboard woods [21], and summarizes the important criteria for fretboard selection. These results will not only help identify alternative timbers for fretboards in the future, but also provide the guidelines for improving the surface color and physical and mechanical properties of fast-growing plantation wood to match the precious woods.

## Materials and methods

### Materials

The heartwood of three tropical hardwood species and one control was analyzed: ebony (*Diospyros crassiflora* J. Kenig ex Retz., from Indonesia), Indian rosewood (*Dalbergia latifolia* Roxb., from Indonesia), African blackwood (*Dalbergia melanoxylon* Guill. & Perr., from Tanzania), and hard maple (*Acer saccharum*, from the United States). The wood (1.5 m in length) was taken from the main trunks of three trees approximately 50 cm in diameter at breast height. The wood was provided by a string instruments' manufacturer. The sizes of samples were $5 \times 5 \times 5$ (all dimensions are presented as the radial $(R) \times$ tangential $(T) \times$ longitudinal $(L)$ in units of mm) for measuring anatomical features; $20 \times 20 \times 20$ for density; $20 \times 20 \times 300$ for the modulus of elasticity (MOE), modulus of rupture (MOR), and impact toughness; $50 \times 50 \times 70$ for hardness tests; $7 \times 7 \times 15$ for the hardness test of wood cell walls, $20 \times 100 \times 100$ for tribological properties; and $20 \times 50 \times 50$ for wood color analysis.

### Measurement of anatomical features

Before microstructure observation, three samples of each species were softened in a boiling mixture of water, glycerin, and ethanol (1:1:1) for 30 days. Then, the samples were cut into 20-μm-thick slices along the tangential and cross-directions using a sliding microtome. These slices were stained using safranin to make permanent sections for the measurement of anatomical characters. We used a Leica DM 2000 microscope connected to a digital camera (Leica DFC 295) and attached to a personal computer to acquire the microscopic images. Images of the entire cross-section were recorded with × 20 and × 10 magnifications, and then connected into a single image. The ImageJ software was used to analyze the vessels and rays per mm in the individual images for the tangential sections.

The ray ratio ($R_r$) was calculated using the following equation [22]:

$$R_r = H/W \tag{1}$$

where $H$ is the height and $W$ the width of a particular ray on the tangential section.

The percentage ($V_C$) of cell wall and the porosity percentage ($V_H$) of wood samples were computed using the following equations [23, 24]:

$$V_C = \frac{\rho_0}{\rho_C} \times 100 \tag{2}$$

$$V_P = 100 - V_C \tag{3}$$

where $\rho_0$ is the oven-dry density and $\rho_C$ the density of the cell wall.

### Physical and mechanical property measurements

The physical and mechanical properties of wood samples were tested according to the methods described in ISO 3129 [25]. All tests were performed after 3 weeks of stabilization at 20 ± 1 °C and 65 ± 2% relative humidity (*RH*) control conditions.

The air-dry density was measured according to ISO 13061-2 [26]. The water uptake and wetting properties were obtained using 10 replicates of cubic samples according to ISO 13061-15 [27] and ISO 13061-16 [28], respectively. Water uptake was used to characterize the water repellency. Oven-dry samples were soaked in deionized water for 20 days at indoor temperature and weighed at regular time intervals after removing excess water with a piece of tissue paper. Water uptake of the sample was calculated based on the weight difference.

To evaluate the mechanical properties of the wood samples, their MOE, MOR, and impact bending strength were measured according to ISO 13061-4 [29], ISO 13061-3 [30], and ISO 13061-10 [31], respectively. The MOE and MOR under static three-point bending were measured using a universal testing machine (Model AG-2000A, Shimadzu Corp., Japan). The impact bending strength was measured using a pendulum impact machine. Thirty samples were used for each of the above mechanical tests.

### Nanoindentation

Nanohardness was measured by nanoindentation using a Hysitron Tribo Indenter equipped with a cube-corner indenter tip. All indentation experiments were performed with a Berkovich head having a needle radius of less than 100 nm, a loading speed of 40 nm/s, and a peak load of 400 μN. In the load control mode, a minimum of 20 effective indentations were made on the cell walls and resin using a three-segment load ramp: loading time of 5 s, hold time of 5 s, and unloading time of 5 s [32, 33]. The standard Oliver–Pharr method was employed to assess the nanohardness, using the relationship between the load and the area of contact for each individual nanoindentation [34]:

$$H = \frac{F_{\max}}{A} = \frac{F_{\max}}{24.5h_c^2} \tag{4}$$

where $F_{\max}$ (μN) is the peak load, $A$ (nm$^2$) the contact area between the indenter and the specimen, and $h_c$ (nm) the depth of the presser head.

The test area and procedure are shown in Fig. 1. To reduce the impact of individual differences among the samples, two test areas, each containing ten test points, were selected on the wood. After the test, the shape and position of the indentations were further screened, and the standard indentation was selected for data analysis.

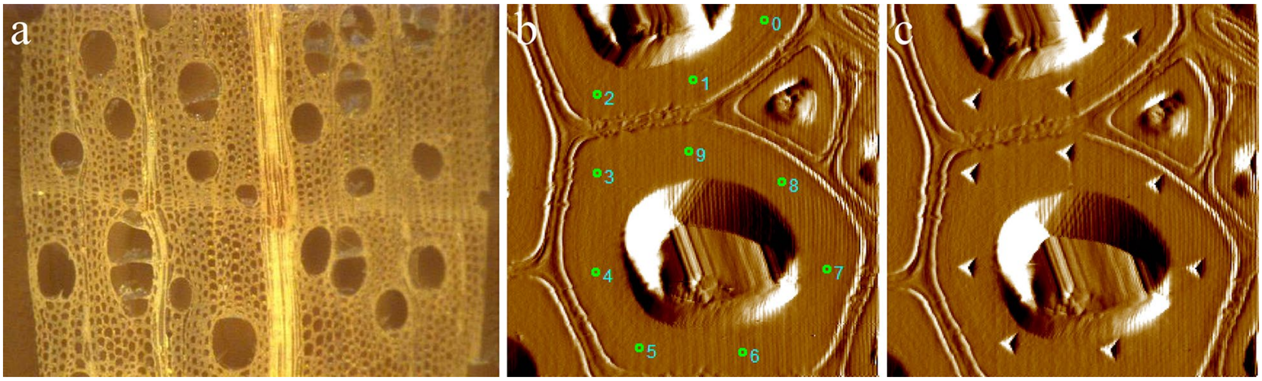

**Fig. 1** Process of nanoindentation testing. **a** Selection of test areas; **b** selection of test points; **c** indentation after unloading

The macro-hardness of wood samples was tested according to ISO 3350:1975 [35]:

$$H_w = KP(N) \tag{5}$$

where $K = 4/3$ is a constant (the depth of pressing is 2.82 mm), $P(N)$ is the $P$ (indentation head load of vertical to the texture) load of steel hemisphere pressed into specimen $N$.

The wear resistance of the wood samples was assessed with a Taber wear-resisting instrument. The specimen was supported on the disk with a horizontal rotation speed of 50 ± 2 rpm. The abrasion performances of the four kinds of wood were compared under different revolutions [36]:

$$F = \frac{m_1 - m_2}{R} \times 100 \tag{6}$$

where $F$ is the abrasion value [in units of mg/100 $r$ (rotations)], $m_1$ and $m_2$ are the specimen mass before and after wear test (mg), respectively, and $R$ is the abrasion revolutions (100 $r$, 200 $r$, 300 $r$, 400 $r$, and 500 $r$).

### Color determination

The surface color of specimens was measured using a colorimeter (Japan MINLTA CR-400 desktop) with a measuring equipment, which had a D65 standard light source, 0/d (vertical lighting/diffuse reflection). The CIELAB (Commission Internationale d' Eclairage) color space defined in 1976 was used to describe the colors [37] using three parameters: the $L^*$, a*, and $b^*$ co-ordinates represent the lightness, red/green color pair, and yellow/blue color pair, respectively. Five test pieces were taken for each tree species. Each test piece was measured at ten points and the average value was reported.

## Results and discussion

### Wood microstructure analysis

The anatomical structure of wood is formed during tree growth and mainly affected by site conditions. Generally, it can only be controlled through the cultivation of forests. Once formed, it is not easy to change the microstructure through improvement methods. The anatomical structures of the three precious woods share common features, which provide a scientific basis for finding the best substitute wood for the fretboard.

All the selected species are diffuse-porous woods. As shown in Table 1, Indian rosewood has the largest vessel diameter. The three fretboard woods have a smaller number of vessels than maple (Table 1), and have dark gum in their pores (Fig. 2). Ebony, Indian rosewood, and African blackwood have slightly thicker fiber cell walls and smaller fiber lumen diameter compared to maple. Table 2 and Fig. 3 summarize the characteristics of rays of the four kinds of wood. Storied and fine rays were observed in all the woods. Ebony had the highest average ray height (330.4 μm), while the ray height of maple varied greatly (25.8–656.1 μm). The average ray width in the three fretboard woods was ~ 25 μm. The ray proportion of ebony, Indian rosewood, African blackwood, and maple was 14, 6, 5, and 7, respectively, with the largest ratio observed in ebony. African blackwood differed from the other species, especially in the higher number of rays per square millimeter, while maple had the lowest number. Due to the potential correlations between the anatomical properties of wood and its physical, mechanical, and acoustic vibration properties, analysis of wood anatomical properties provides a theoretical basis for the selection of wood materials in musical instruments [22, 38, 39].

### Physical and mechanical properties

Different types of musical instruments and their various components have different requirements in the wood density. For the soundboard of string instruments, when the wood density falls in the range of 0.4–0.5 g/cm$^3$, its dynamic elastic modulus will be larger, its loss tangent value will be smaller, its acoustic vibration efficiency will be higher, and the sound of the instrument will be louder and clearer [20, 40]. The backboard and ribs of string instruments are often made of medium-density maple with an air-dry density of 0.69 g/cm$^3$. In contrast, the density of ebony, Indian rosewood, and African blackwood used for fretboard is much higher (1.21, 0.81, and 1.36 g/cm$^3$, respectively). Generally, the wood used for fretboard should have a density greater than 0.80 g/cm$^3$ to achieve high hardness and strong wear resistance.

**Table 1 Wood vessel and fiber characteristics**

| Species | Vessel diameter/μm | Number of vessels/mm$^2$ | Fiber wall thickness/μm | Fiber lumen diameter/μm |
|---|---|---|---|---|
| Ebony | 74.5 (16.40) | 10 (3.69) | 3.5 (0.82) | 6.3 (2.14) |
| Indian rosewood | 134.4 (23.30) | 15 (3.03) | 3.4 (0.89) | 4.5 (2.95) |
| African blackwood | 80.1 (25.60) | 13 (3.96) | 3.2 (0.82) | 5.7 (2.65) |
| Maple | 72.2 (11.09) | 56 (3.23) | 2.9 (0.84) | 6.6 (1.65) |

Standard deviations are shown in parentheses

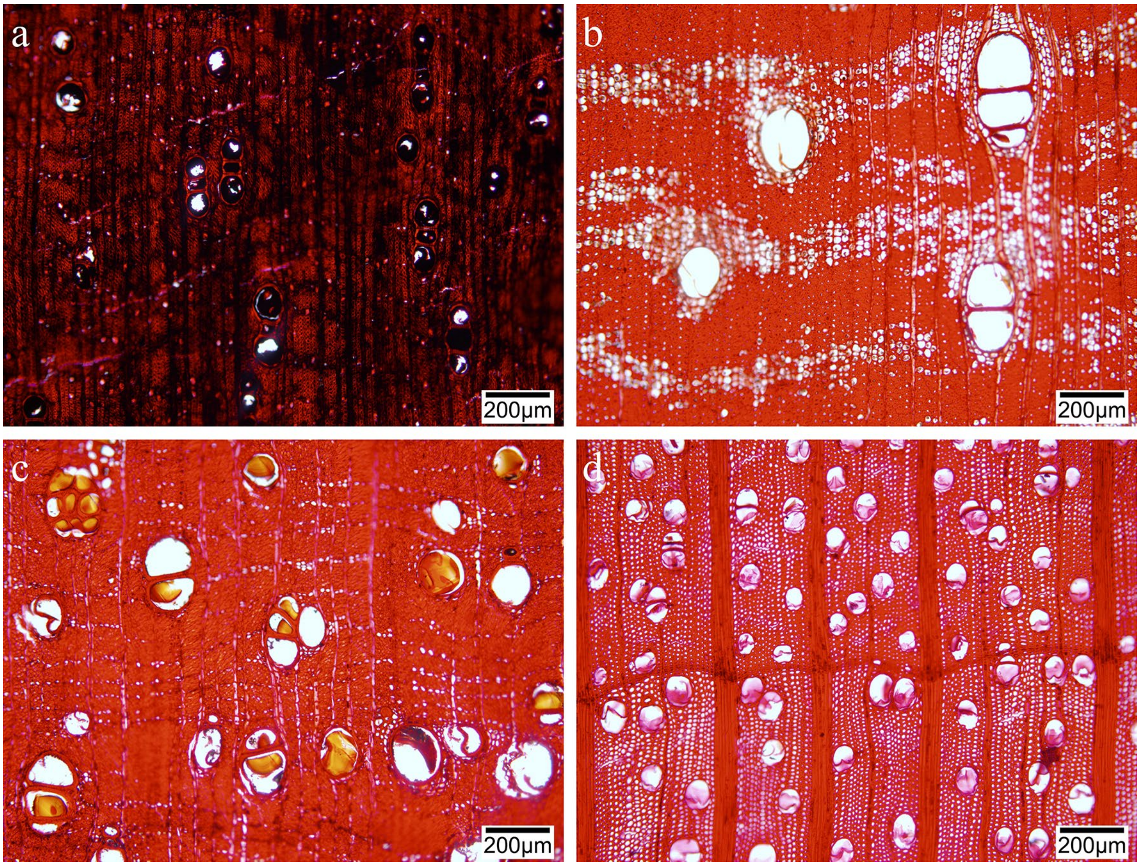

**Fig. 2** Cross-sections of different types of wood: **a** ebony; **b** Indian rosewood; **c** African blackwood; **d** maple. Scale bars 200 µm

**Table 2 Wood ray characteristics**

| Species | Ray height/µm | Ray width/µm | Ray ratio | Number of rays/mm |
|---|---|---|---|---|
| Ebony | 330.4 (88.30) | 24.1 (14.12) | 14 (7.57) | 15 (1.91) |
| Indian rosewood | 146.5 (23.19) | 25.3 (7.62) | 6 (2.14) | 11 (1.71) |
| African blackwood | 118.6 (54.47) | 22.5 (7.23) | 5 (2.13) | 17 (3.03) |
| Maple | 225.7 (172.54) | 34.1 (26.15) | 7 (6.01) | 10 (2.12) |

Standard deviations are shown in parentheses

Wood is naturally hygroscopic, a property that changes with the humidity of the environment. Therefore, the dimensional stability of wood used in string instruments is very important [41]. The moisture content of wood also affects its physical, mechanical, and acoustic vibration characteristics. When the moisture content is very high, the dynamic elastic modulus of the wood will decrease, and its loss tangent will increase. This creates internal stresses due to the volume change, which influences the sound quality of the instrument and the sounding effect becomes unstable. Conversely, woods with better dimensional stability lead to a more stable overall sounding effect of the instrument [42].

Here, we measured the volumetric swelling coefficient (VSW), tangential linear swelling coefficient (TLSW), and radial linear swelling coefficient (RLSW) of the four woods, from the oven-dry state to air-dry state and from the oven-dry state to the water-saturated state. The results, shown in Fig. 4, suggest that the four types of wood have significant differences in their anti-hygroscopic capacity. Figure 4a shows the dimensional change rate of wood at 20 ± 1 °C and 65 ± 2% RH conditions. The VSW values of moisture absorption in ebony, Indian rosewood, African blackwood, and maple were 4.64, 4.25, 0.37, and 4.72%; the TLSW values were 2.56, 1.97, 0.16, and 2.7 4%; and the RLSW values were 1.81, 1.88, 0.03, and 1.74%, respectively. Figure 4 b shows the dimensional change rate of wood when it is saturated with deionized water. The VSW values of water absorption were 15.12, 12.65, 6.43, and 17.04%; the TLSW values were 8.59, 6.32, 3.22, and 10.41%; and the RLSW values were 5.44, 5.14,

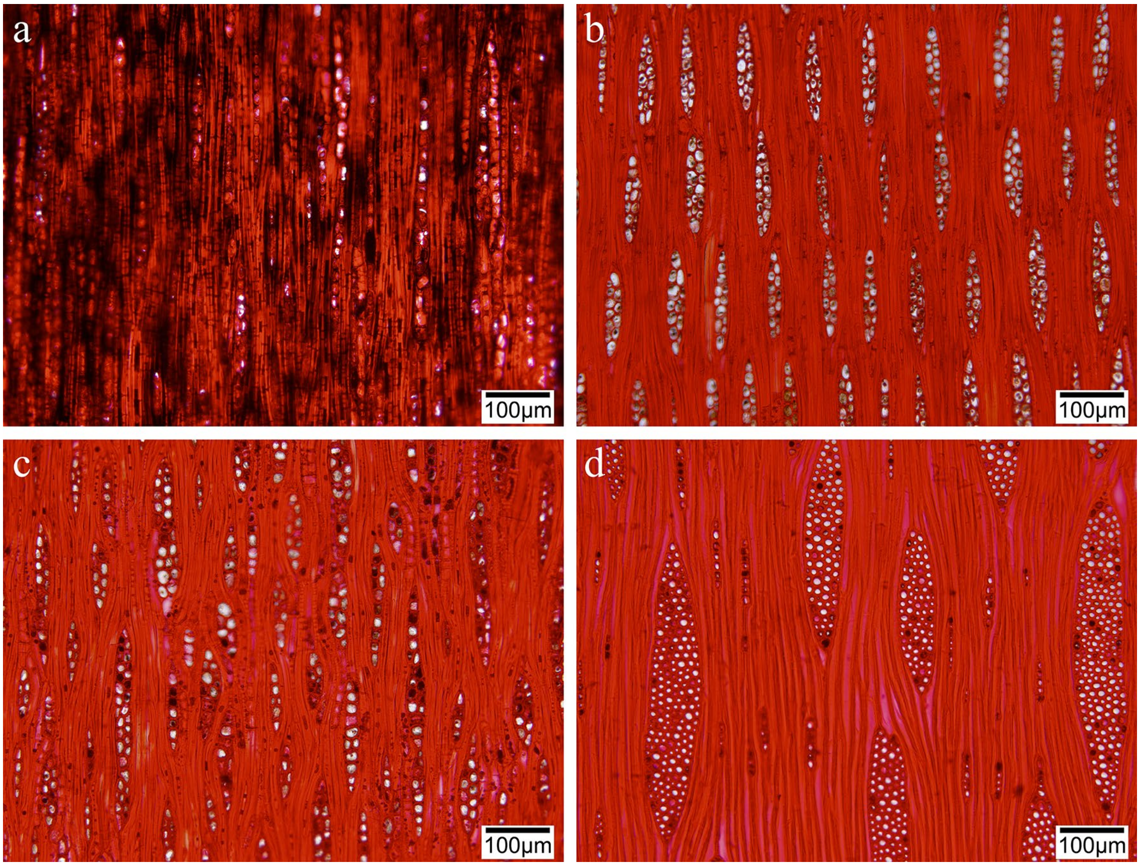

**Fig. 3** Tangential sections of different types of wood: **a** ebony; **b** Indian rosewood; **c** African blackwood; **d** maple. Scale bars 100 μm

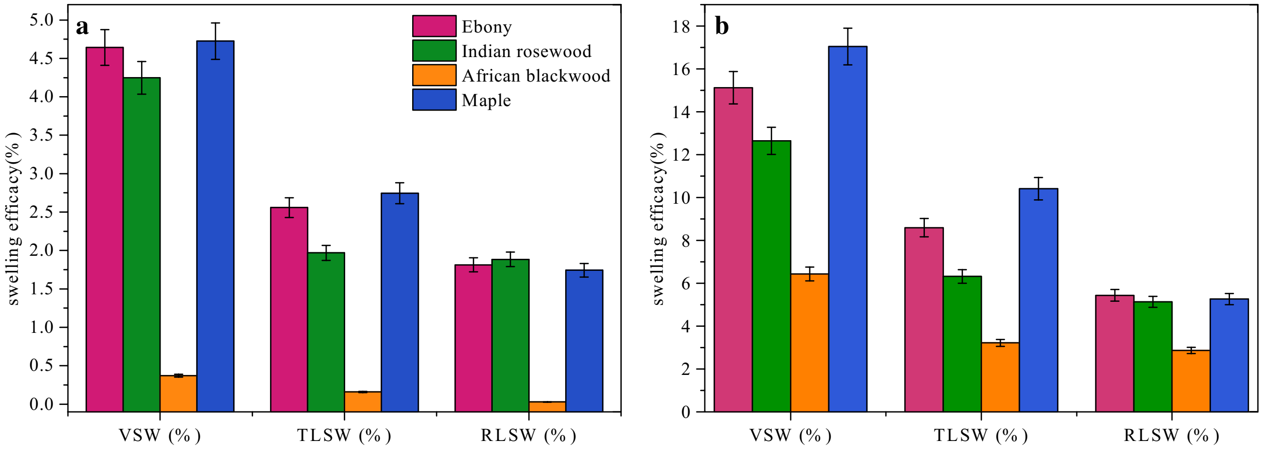

**Fig. 4** Wood swelling efficiency. *RLSW* radial linear swelling coefficient, *TLSW* tangential linear swelling coefficient, *VSW* volumetric swelling coefficient

2.87, and 5.26%, respectively. African blackwood had the smallest swelling coefficient, meaning that it had the least dimensional change and maximum dimensional stability, both in high humidity environments and when immersed in water. Recall that the density of African blackwood is high, with thick fiber cell walls, small cavities, the smallest vessel diameter, and a large amount of gum in the pores. As a result, it has a lower capacity for water storage. Compared to the fretboard woods, maple has a higher swelling coefficient, and so its dimensional stability is poor.

Figure 5 shows the water uptake of the four woods after soaking in deionized water for 1, 2, 4, 8, 16, and 20 days, until the wood was saturated. The water uptake can be ranked as maple > ebony > Indian rosewood > African blackwood, and this trend was consistent with the wood swelling coefficients shown in Fig. 4. Maple showed a weight gain of ~ 105% upon soaking in water for 20 days, while the gains of the fretboard woods were one-third or less of this value. For the first 2 days of soaking, the water uptake rate of maple increased sharply with the soaking time. As mentioned before, maple has a low density, and its numerous cross-section vessels promote the transport of moisture. As a result, it absorbed water quickly. The water uptake of African Blackwood was lower, which is mainly due to its high density, fewer pores per square area, and the fact that most of the pores contain gum. The swelling coefficients from moisture absorption and water absorption are both lower for the fretboard woods compared to maple.

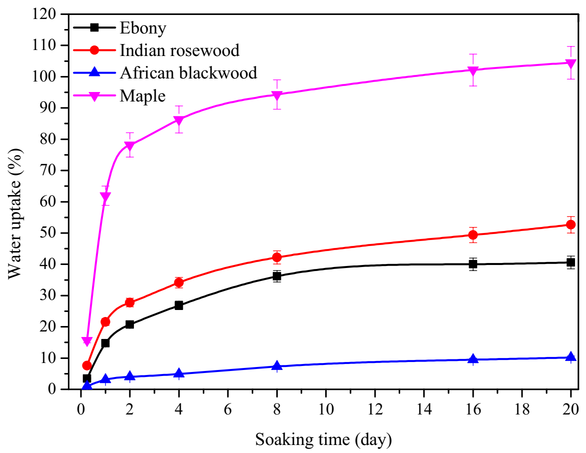

**Fig. 5** Wood water uptake

During the plucking and vibration processes, the strings apply tension to the neck of the string instrument, making the latter prone to bending and twisting deformation. As a result, the fretboard can fall off the neck. The greater the static bending strength and stiffness of the fretboard material, the better ability for the fretboard to resist the bending and twisting deformation [20]. Conversely, fretboards made of wood with smaller MOR and MOE values will experience a greater degree of bending deformation. The MOE and MOR values were the highest for African blackwood (17.9 GPa and 190.8 MPa, respectively), the lowest for Indian rosewood, and those for ebony and maple were similar.

Woods with a higher bending strength and elastic modulus can improve the performance of musical instruments. The impact bending strengths of ebony, Indian rosewood, African Blackwood, and maple are listed in Table 3. This value was smallest for ebony, while that of African blackwood was larger. Wood with a lower impact toughness tends to be brittle and vulnerable to brittle damage, thus affecting the aesthetics of the instrument.

Since the fretboard comes into contact with the vibrating strings and fingers during playing, wood with superior wear resistance could ensure the accurate and consistent positioning of notes on the fretboard [12]. Csanády et al. classified the wear resistance (abrasion resistance) of wood into three grades [24]: satisfactory (150–220 mg/100 *r*), good (80–150 mg/100 *r*), and very good (< 80 mg/100 *r*). The abrasion resistances of ebony, Indian rosewood, African blackwood, and maple were 113, 101, 87, and 97 mg/100 *r*, respectively. While African blackwood had the best wear resistance and ebony the worst, all four types of wood fall within the "good" category according to the above classification [43].

Wood used in fretboards must have adequate density and hardness, before other performance indicators could be assessed. When the instrument is played, the fretboard should effectively resist the tension of strings and the compressive force from the player's fingers, while minimizing deformation and the formation of surface pits. The rigidity of the neck can change the main resonance frequency of the soundboard within a small range.

**Table 3 Mechanical properties of wood**

| Samples | *P* (g/cm$^3$) | MOE (GPa) | MOR (MPa) | Impact bending strength (kJ/m$^2$) | Wear resistance (mg/100 *r*) |
|---|---|---|---|---|---|
| Ebony | 1.21 (0.01) | 16.4 (0.51) | 157.4 (2.11) | 25.9 (3.53) | 113 (0.01) |
| Indian rosewood | 0.83 (0.01) | 14.1 (1.69) | 149.3 (3.91) | 46.4 (1.30) | 101 (0.01) |
| African blackwood | 1.36 (0.01) | 17.9 (1.04) | 190.8 (9.36) | 50.2 (2.51) | 87 (0.00) |
| Maple | 0.69 (0.01) | 16.7 (0.91) | 133.8 (9.26) | 46.9 (2.67) | 97 (0.01) |

Standard deviations are shown in parentheses

When the main resonance frequency is reduced by only 10 Hz, one can tell the difference between instruments of the top and second-tier quality [13, 44]. Fretboards made with very soft wood cause a less stiff neck and a reduced main resonance frequency, making the expression of the instrument weak and uneven. Conversely, a harder fretboard material can help suppress the main resonance frequency shift and improve the vibration amplitude of the soundboard, so that the expression of the instrument is enhanced and uniform. From the perspective of vibration conduction through the neck, if the neck is regarded as a low-frequency channel, the fretboard acts as a high-frequency channel to widen the overall conduction band of the neck. The fretboard is glued to the neck mainly by the compressive force, at which a good conductivity for high-frequency sound waves can be achieved only if the stiffness is high. Meanwhile, the neck material should have considerable but not excessive hardness.

In this study, the microscopic and macroscopic hardness of four woods were compared and the corresponding requirements for fretboard wood selection were discussed. Figure 6 is a box diagram of the nanohardness for the cell walls. Nanoindentation was performed on both the $S_2$ layer of the secondary cell wall and the middle lamella of wood samples [34]. The cell wall hardness of ebony, Indian rosewood, and African blackwood was 0.564, 0.469, and 0.500 GPa, respectively, while that of maple was considerably lower (0.413 GPa).

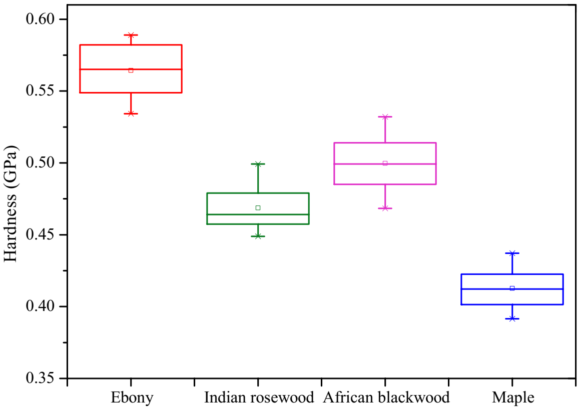

**Fig. 6** Wood nanoindentation hardness. The lower horizontal line of the inverted letter T is the minimum; the upper horizontal line of the letter T is maximum; the big square bottom edge represents the 1st quartile; the big square upper edge represents the 3rd quartile; the horizontal line inside the large square represents the median; small squares are average values; the *sign outside the box indicates an outlier

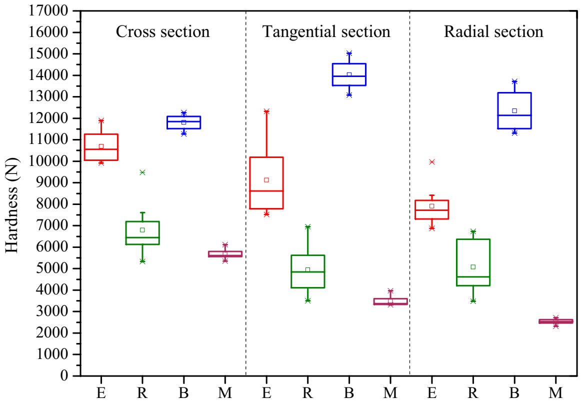

**Fig. 7** Hardness of wood. *E* denotes Ebony, *R* Indian rosewood, *B* African blackwood, and *M* Maple. The *sign outside the box indicates an outlier. When the expected data of the group were calculated, the outlier was removed

Figure 7 further compares the hardness on three different sections of each wood: the cross-section, the tangential section, and the radial section. In all samples except for African blackwood, the hardness is ranked as cross > tangential > radial section. Thus, the flat-sawn board is mainly used for the fretboard. African blackwood has the highest hardness, with values of 15.5, 18.7, and 16.5 kN, respectively. The second hardest wood is ebony (14.3, 12.2, and 10.5 kN, respectively), and those values for Indian rosewood are 9.1, 6.6, and 6.8 kN. The hardness values of the tangential and radial sections of ebony and African blackwood were similar and about 1.5 times that of Indian rosewood. In comparison, maple had the lowest hardness in all three sections (7.6, 4.7, and 3.4 kN, respectively). Again, the superior hardness of the three fretboard woods can be attributed to their high density, fewer tube holes per area, and larger fiber walls. In string instruments, maple is mainly used for the back and rib board, which have lower requirements on the wood hardness. Overall, wood used for the fretboard should have a hardness of more than 9.0 kN in the cross-section, and more than 6.0 kN in the tangential and radial sections.

In terms of physical and mechanical properties, the wood density, moisture content, hygroscopicity, dimensional stability, hardness, modulus of rupture, and wear resistance are all important criteria for fretboard wood selection. In this paper, these characteristics were measured on three kinds of commonly used fretboard timber and compared to those of maple. Such information will help the functional improvement of fast-growing wood to replace traditional fretboard woods.

## Wood color

The fretboard of string instruments is usually black or dark brown in color to accommodate traditional aesthetic requirements; while the soundboard, backboard, and ribs are mainly made of beige or light-yellow colored spruce and maple. The heartwood color of ebony and African blackwood is jet black or dark brown and uniform (Fig. 8). In comparison, Indian rosewood can appear as brown black, purplish brown, or deep purple-red.

Compared to subjective human observation, the color of wood samples can be assessed objectively using colorimetry [20]. Here, the wood surface color was characterized by a colorimeter and expressed in the ($L^*$, $a^*$, $b^*$) chromaticity space. $L^*$ is the brightness, $a^*$ the red-green index, and $b^*$ the yellow-blue index [45].

According to Fig. 9, the brightness value $L^*$ of the traditional fretboard woods was relatively low in the range of 20–30 (those for ebony, Indian rosewood, and African blackwood were 20.86, 29.17, and 21.89, respectively). In contrast, the $L^*$ value of maple was about three times higher (69.69). The $a^*$ values of ebony, Indian rosewood, African blackwood, and maple were 0.72, 6.27, 1.46, and 5.74, respectively. The $b^*$ values were also positive, indicating that the wood colors were more yellow than blue. Not surprisingly, maple had a relatively large $b^*$ value of 14.26, while that of ebony, Indian rosewood, and African blackwood was 0.92, 5.58, and 1.28, respectively.

Considering the measured $L^*$, $a^*$, and $b^*$ values for ebony, Indian rosewood, and African blackwood, we determined that their suitable replacements should have an $L^*$ value below 30, and a $b^*$ value below 6.0. These criteria are useful for deciding which potential substitute (natural wood or after modification) better matches the three fretboard woods in color.

## Conclusions

We studied the anatomical structure and physical and mechanical properties of tropical hardwood species that are commonly used in the fretboard of string instruments. Based on the measured data, a set of performance

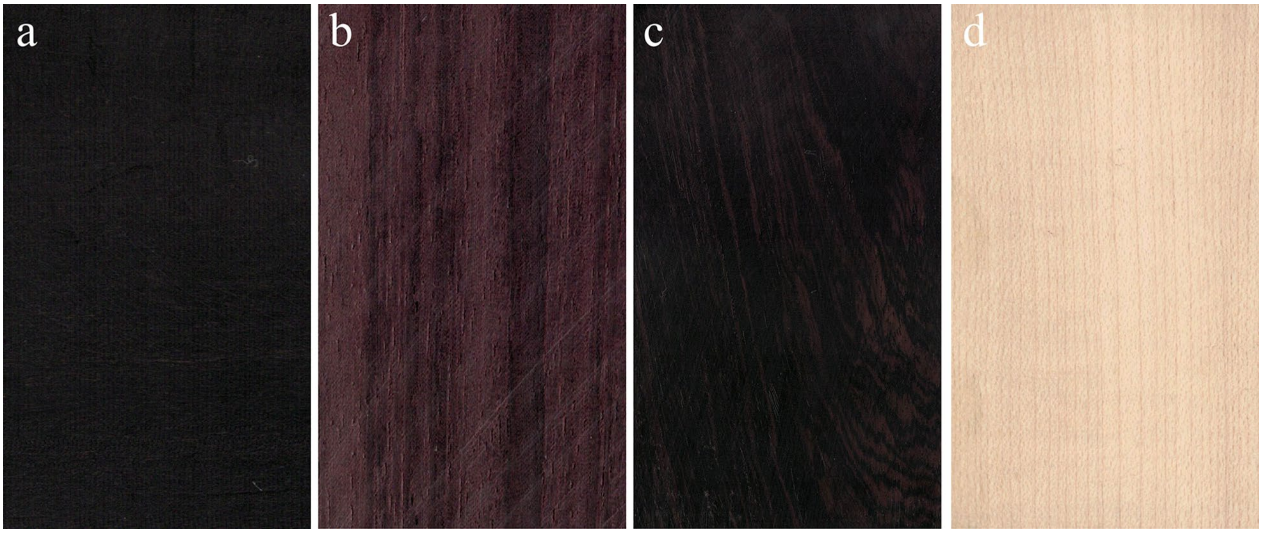

**Fig. 8** Photographs showing the appearance of individual species. **a** Ebony; **b** Indian rosewood; **c** African blackwood; **d** maple

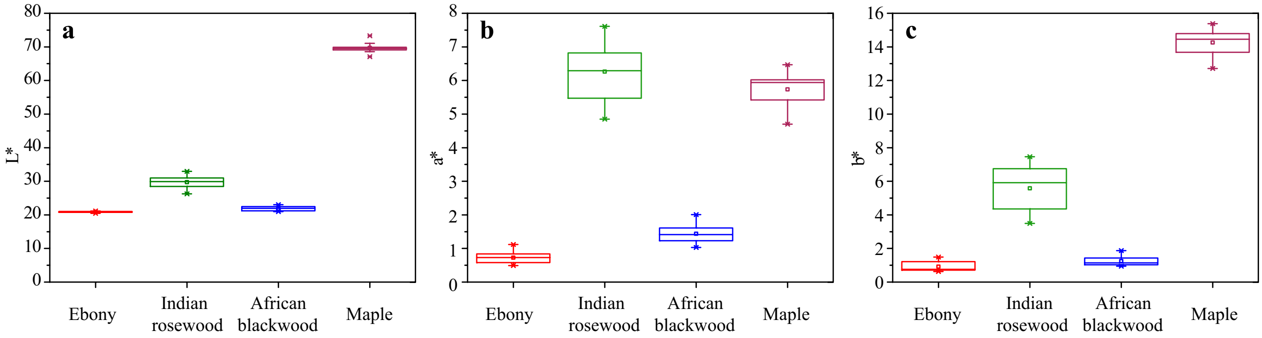

**Fig. 9** Colorimetric parameters ($L^*$ (lightness), $a^*$ (red/green color pair), and $b^*$ (yellow/blue color pair)) of the four wood species

indices was established for screening wood materials that could replace the precious wood in the fretboard.

The substitute wood species should be tropical diffuse-porous hardwood, with a density greater than 0.80 g/cm$^3$ and a uniform texture. It is required to have ultra-fine dwarf ray, very few pores, and small pore diameters. Further, the wood should have low porosity and thick fiber walls with a cell wall rate exceeding 50%. The wood surface color should be jet black or purplish brown. For stability during use and storage, the water absorption swelling coefficient and water uptake of the wood should be low, and its dimensional stability should be high. Quantitatively, the hardness of the wood must exceed 9.0 kN for the cross-section and 6.0 kN for the tangential and radial sections; the modulus of rupture and elasticity should be higher than 149 and 14.08 GPa, respectively. The optimal wear resistance is 80–150 mg/100 *r*. Finally, the wood should have a certain impact bending strength to prevent brittle damage. The above criteria provide a scientific basis for developing physical, chemical, and biological methods to modify fast-growing plantation wood to replace the traditional fretboard wood.

When modifying non-instrument fretboard wood, the modified fast-growing plantation wood should have similar or superior performance and appearance compared to traditional fretboard woods.

### Abbreviations

MOE: Modulus of elasticity; MOR: Modulus of rupture; RLSW: Radial linear swelling coefficient; TLSW: Tangential linear swelling coefficient; VSW: Volumetric swelling coefficient.

### Acknowledgements

The authors are grateful for the financial support from National Key Research and Development Program of China (2017YFD0600202).

### Authors' contributions

ML designed the study and wrote the manuscript. JL, LP, and SL performed the research and analyzed the data. JL supervised the project. All authors read and approved the final manuscript.

### Funding

This research was sponsored by the National Key Research and Development Program of China (2017YFD0600202).

### Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

### Competing interests

The authors declare that they have no competing interests.

Received: 9 October 2019 Accepted: 26 February 2020

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