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Wood color analysis and integrated selection of *Paulownia* clones grown in Hubei Province, China

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Abstract. *Paulownia* Siebold et Zucc., a widely distributed native genus, has been commonly used in the furniture. The color of wood is a very important aesthetical property, and it has a fundamental influence on the commercial value of timbers. Therefore, it is critical for forest managers to select elite *Paulownia* clones based on the color of wood. Eighteen 5-year-old *Paulownia* clones grown in a hilly area in Hubei Province, China were examined in terms of color values (L^*, a^*, b^*), color difference (ΔE^*), and Hunter lab space whiteness (W) using a Chroma meter CR-400. Differences in color parameters among the 18 clones were analyzed and clustered. The results showed that the ranges of L^*, a^*, b^*, ΔE^*, and W were 77.19–80.38, 3.60–4.84, 13.79–15.69, 17.92–21.37, and 68.92–72.42, respectively. The color parameters significantly differed among the examined clones. Differential and cluster analyses indicated that clones 204, 605, 702, and 603 had higher L^*, W, and lower ΔE^*, rendering these as elite clones with superior color properties.

Key words: Lower hilly region, *Paulownia*, clones, wood color characteristics.

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Introduction

Paulownia Siebold et Zucc. is a multipurpose native genus that is extensively grown in China. It is a deciduous fast-growing plant and produces high-quality timber. It also has several applications, particularly for agroforestry (Jiang, 1990; Ru, 2004). *Paulownia* timber has numerous characteristics, including being lightweight, soft, pale-blonde color with a silky sheen, easily processed and dried, strong and stable, warp-resistant, and splinter-resistant. Because of these features, it has been widely used in the furniture, interior decoration, and various other industries. Currently, the *Paulownia* cultivation area in China is expanding southwards, which has consequently resulted in the selection of easy-to-grow *Paulownia* clones with high-quality timber.

Wood color is a very important aesthetical property, and it has a fundamental influence on the commercial value of timbers (Liu, 1994; Liu *et al.*, 1995; Huang *et al.*, 2009; Li, 2010). Color is an important factor in finding uses for wood, and the quality of wood is sometimes evaluated by its color. However, wood discoloration, which is defined as an abnormal color pattern that

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generally occurs during timber harvesting, sawing, drying, and other processes that leads to dark brown or black brown spots on its surface. Such discoloration may directly affect a customer's choice of furniture or other wood-based product, thus indirectly resulting in economic problems in the wood industry (Nishino *et al*., 1998; Duan, 2002, 2005; Weigl *et al*., 2009; Teischinger *et al*., 2012; Forsthuber *et al*., 2013). Previous studies have shown that the color of *Paulownia* timber, especially whiteness, significantly differs among various species, origin, clones, and even individual plants (Zu & Zhou, 1998; Wang *et al*., 1999; Ru *et al*., 2007; Zhai *et al*., 2012; Chang *et al*., 2013; Qiu, 2013). The color properties of *Paulownia* are apparently independently inherited and not associated with other phenotypes (Xu & Kang, 1994; Wu, 2000; Wu *et al*., 2003). This mode of inheritance thus allows the use of directional breeding to generate *Paulownia* clones with superior color properties. The color of *Paulownia* wood affects its market value and applications: wood with superior color properties (high luminosity, high whiteness, low color difference, and even color distribution) is of higher value and can be further processed into high-quality decorative materials. However, current studies on the color of *Paulownia* wood have mainly focused on a single whiteness parameter or comparison of several simple parameters. Moreover, various other factors, including varieties of color parameters, differences in wood color evaluation indices, and the uncontrollability of sampling, have impeded the selection of elite *Paulownia* clones with superior color properties. In the present study, we used 18 5-year-old *Paulownia* clones grown in a hilly area of Hubei Province and measured five color parameters, including lighteness (L^*), redness/greenness (a^*), yellowness/blueness (b^*), color difference (ΔE^*), and Hunter lab space whiteness (W). These parameters were further analyzed and compared. The aim of this study was to select elite *Paulownia* clones that possessed superior color properties and were suitable to grow in local areas.

Material and Methods

Study sites

The study was performed in Shicheng town, Xianning city, Hubei Province China. The plant site is a typical hilly area, with an altitude of 180 m, and a slope ranging from 15º to 25º. The soil was yellowish red with medium loam texture. The area has subtropical monsoon climate with ample sunshine and plenty rainfall. Its average temperature, average annual rainfall, and relative humidity were 15.8 °C, 1988.5 mm, and 80%, respectively. Its natural vegetation mainly included Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), oak (*Quercus* L.), *Lespedeza* Michx., and *Miscanthus* Andersson dominated savanna shrub, and small mine bamboo (CV. *Ventricousinternode*). The site was prepared into a terrace in the spring of 2008. The previously collected and selected clones with a pile of roots (1-year-old, with a base diameter of 3–4 cm) were used in afforestation. A randomized complete block design was utilized (Figure 1). Each clone had 3 replications. There were 6 plants in each replication, with a spacing of 4 m × 5 m. Singling of seedlings, pruning, fertilization, trimming, and other nurturing care were similarly performed for all the clones. The increase in height, diameter, and number of branches in each clone was regularly recorded. By 2013, when all the clones were cut down, and the average trunk height, average first graft height, and average chest diameter was 3.5 ± 0.8 m, 4.5 ± 0.9 m, and 18.0 ± 2.3 cm, respectively.

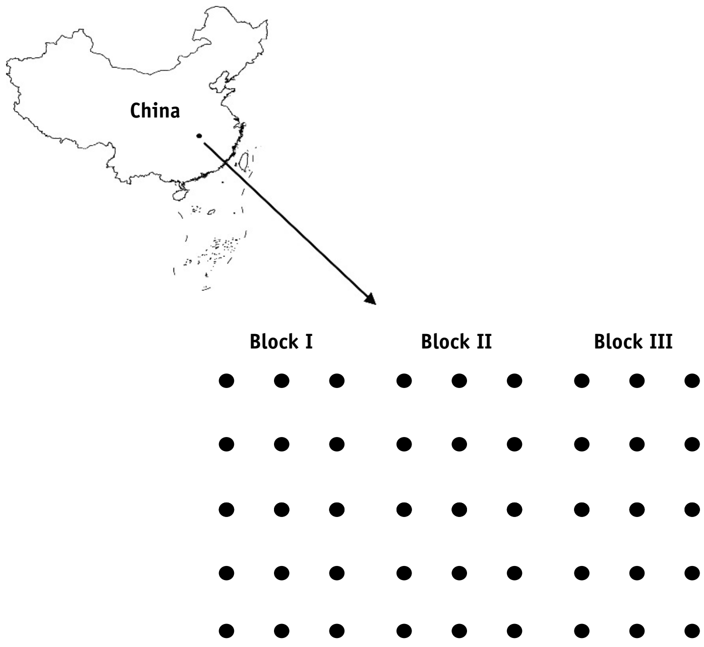

Figure 1. Study location and experiment design. Each dark spot denotes the *Paulownia* clone.

Methods

Among 18 *Paulownia* clones, 17 elite clones were selected based on their fast-growing feature in the North China Plain region during the 11th five-year scientific and technological improvement plan. The control clone was *P. fortunei* (Seem.) Hemsl. (CK), a local species distributed in Hubei Province. The detailed information on the sources of these clones is listed in Table 1. Based on the source, 17 clones were classified into four categories, namely *P. tomentosa* (Thunb.) Steud., *P. fortunei*, *P. elongata* S.Y. Hu, and *Paulownia* hybrids.

Table 1. Information about 18 clones of *Paulownia*.

Clone no.	Clone source	Clone no.	Clone source
101	plus tree of *P. tomentosa*	601	*P. tomentosa*×*P. fortunei*
102	seedling selection in *P. tomentosa*	603	*P. tomentosa*×*P. fortunei*
201	plus tree of *P. fortunei*	604	*P. tomentosa*×*P. fortunei*
203	plus tree of *P. fortunei*	605	*P. tomentosa*×*P. fortunei*
202	seedling selection in *P. fortunei*	606	*P. tomentosa*×*P. fortunei*
204	seedling selection in *P. fortunei*	607	*P. tomentosa*×*P. fortunei*
205	seedling selection in *P. fortunei*	608	*P. tomentosa*×*P. fortunei*
209	seedling selection in *P. fortunei*	702	*P. tomentosa*×*P. fortunei*
301	plus tree of *P. elongata*	CK	plus tree of *P. fortunei*

Representative *Paulownia* trees were selected from each plantation site. Three 8-cm long samples were collected from the sites of each tree: at the base, 1.3 m above the base, and 2.6 m above the base. Then, four specimens from each sample were prepared, with the following dimensions = 70 mm × 50 mm × 12 mm (longitudinal × radial × tangential size), and air-dried for color parameter measurements. A Chroma Meter CR-400 (Konica Minolta) and standard D65 illumination was used, and color parameters were determined using the CIELab system. The tristimulus values (*X*, *Y*, and *Z*) of both sides were determined for each sample. Based on the color index requirement of commercial application of *Paulownia* wood and the results of our previous studies, the five color parameters, including L^*, a^*, b^*, ΔE^*, and *W* were measured and analyzed. Calculation and analysis were performed using equations (1)–(8).

$$L^* = 116\sqrt[3]{\frac{Y}{Y_n}} - 16 \quad (1)$$

$$a^* = 500\left(\sqrt[3]{\frac{X}{X_n}} - \sqrt[3]{\frac{Y}{Y_n}}\right), \text{ and} \quad (2)$$

$$b^* = 200\left(\sqrt[3]{\frac{Y}{Y_n}} - \sqrt[3]{\frac{Z}{Z_n}}\right) \quad (3)$$

where X_n, Y_n, and Z_n represent tristimulus values of the perfect reflecting diffuser, which were 95.0546, 100.0000, and 108.9258, respectively.

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (4)$$

where ΔL^*, Δa^*, and Δb^* represent differences in the respective values between testing specimens and reference specimen, and for the reference specimen, these were 94.57, -0.39, and 4.31, respectively.

$$W = 100 - \sqrt{(100 - L)^2 + a^2 + b^2} \quad (5)$$

where *L, a,* and *b* represent the lightness, redness/greenness, and yellowness/blueness in the Hunter lab space, respectively.

Where

$$L = 100\sqrt{\frac{Y}{Y_n}} \quad (6)$$

$$a = 175\sqrt{\frac{0.0102\,X_n}{(Y/Y_n)}}\left[\frac{X}{X_n} - \frac{Y}{Y_n}\right] \quad (7)$$

$$b = 70\sqrt{\frac{0.0084\,Z_n}{(Y/Y_n)}}\left[\frac{Y}{Y_n} - \frac{Z}{Z_n}\right] \quad (8)$$

In the CIELab system, L^* indicates the degree of color lightness and serves as an important indicator for *Paulownia* wood quality. Wood with a greater L^* value has a bright surface color and higher commercial value, whereas wood with lower L^* values has a grey and dull surface and therefore lower commercial value. a^* represents the chroma value and defines the position on the red-green axis (+100 values for red shades, -100 values for green shades). The more positive a^* value is, the more reddish the wood is. On the other hand, the more negative the a^* value is, the more greenish the wood is. b^* represents the chroma value and defines the position on the yellow–blue axis (+100 values for yellow shades, -100 values for blue shades). Positive b^* indicates that the wood is more yellowish, whereas a negative value indicate that the wood is more bluish. Greater absolute a^* and b^* values was suggestive of high degree of variability in the natural color of the wood, which in turn significantly affects the color, brightness, and texture of wood, and consequently, the commercial value of the wood. ΔE^* represents color variation and stability (Hiltunen *et al.*, 2008; Oltean *et al.*, 2008; González-Pena &

Hale, 2009; Ibach *et al*., 2010), with higher value indicating more extensive color variation. Low ΔE^* values indicate more stable wood color and higher commercial values.

For each *Paulownia* clone, a total of 36 specimens from 4 directions at 3 locations and from 3 plants were collected. Color parameters were compared using one-way ANOVA and Duncan's post-hoc test. The average values of each color parameter of 18 *Paulownia* clones and the CK reference wood were normalized to 1. Cluster analysis was performed using Euclidean distance and complete linkage (furthest neighbor) methods (Zhou *et al*., 2009; Zhu, 2010; Zhang *et al*., 2015). Data processing and statistical analysis were conducted using Excel 2003 and SPSS 18.0 software.

Results

Differences in color parameters among various *Paulownia* clones

Differences in L^* values among various *Paulownia* clones

One-way ANOVA analysis indicated significant differences in L^* values among the 18 *Paulownia* clones examined (Table 2). However, the range of L^* values, 77.19–80.38, only showed a 4.13% difference between the maximum and minimum values, and its coefficient of variation (CV) was relatively low (1.94%–3.97%). Based on these findings, L^* was considered a relatively stable parameter, and thus posed a lower chance for improvement. Thirteen *Paulownia* clones had higher L^* values than that of CK, with ΔL^* ranging from 0.07% to 2.07%. Duncan's post-hoc test showed that only clones 603 and 702 had significantly higher L^* values than that of CK, with ΔL^* values of 2.07% and 1.55%, respectively. The L^* values of clones 608, 605, 204, 209, and 203 were higher than that of CK (ΔL^* ranged from 0.77% to 1.29%), but did not significantly differ from that of clone 603. These 5 clones were classified as clones with brighter wood color (Table 2).

Differences in a^* values among various *Paulownia* clones

According to ANOVA analysis, the a^* values significantly differed among the 18 *Paulownia* clones (Table 2). It ranged from 3.60 to 4.84. The maximum value was 34.50% higher than the minimum, whereas that of CV ranged from 11.19% to 27.28%. Based on these findings, the a^* value was considered a more variable parameter, thereby offering more options for improvement. Compared to CK, 11 *Paulownia* clones had relatively lower a^* values, with Δa^* ranging from 0.88% to 13.08%. Duncan's post-hoc test showed that *Paulownia* clones 603, 702, and 204 had significantly lower a^* values compared to that of CK, with Δa^* values of 13.08%, 11.74%, and 11.58%, respectively. The a^* value of clone 605 was 6.94% lower than that of CK, whereas it was not significantly different from those of 603, 702, and 204. Therefore, these four clones were classified as clones with higher red/green axis chromaticity indices.

Difference in b^* values among various *Paulownia* clones

One-way ANOVA analysis showed that b^* values significantly differed among the 18 *Paulownia* clones (Table 2). It ranged from 13.79 to 15.69. The maximum was 13.82% higher than the minimum, and that of CV was between 5.67% and 12.65%. Therefore, the b^* value was considered as a relatively stable parameter, thereby offering less room for improvement. Compared to CK, 10 *Paulownia* clones had relatively lower b* values, with Δb^* ranging from 0.13 to 4.49%. Duncan's post-hoc test showed that only clone 702 had a significantly lower b^* value than that of CK (4.49%). The other eight clones, 209, 202, 203, 608, 605, 101, 601, and 204, had lower b* values than that of CK, with Δb^* ranging from 0.67% to 3.57%. However, the b^* values of these

Table 2. Differences in color parameters among various *Paulownia* clones.

Clone no.	L^*	a^*	b^*	ΔE^*	W
101	(79.12±1.92) bcd	(4.40±0.76) bc	(14.18±1.38) defg	(19.02±2.11) de	(71.33±2.24) abc
102	(77.20±2.32) f	(4.41±0.53) bc	(14.62±0.95) bcde	(20.81±2.17) ab	(69.24±2.48) f
201	(77.92±1.78) ef	(4.51±0.71) b	(14.86±1.26) bc	(20.36±1.83) bc	(69.89±1.98) def
202	(78.80±2.34) cde	(4.10±0.81) cde	(14.08±0.80) efg	(19.14±2.15) de	(71.07±2.5) bc
203	(79.50±2.53) abcd	(4.18±1.07)cd	(14.11±1.11) efg	(18.62±2.5) ef	(71.77±2.81) abc
204	(79.51±1.95) abcd	(3.66±0.61) f	(14.34±1.35) cdefg	(18.60±1.99) ef	(71.77±2.18) abc
205	(77.19±2.24) f	(4.33±0.61) bcd	(15.69±1.59) a	(21.37±2.31) a	(68.92±2.49) f
209	(79.50±2.16) abcd	(4.08±0.90) de	(13.92±0.82) fg	(18.46±2.21) ef	(71.86±2.45) ab
301	(79.01±1.79) bcd	(4.02±0.75) de	(14.65±1.30) bcde	(19.27±1.67) de	(71.10±1.89) bc
601	(78.82±2.25) bcde	(4.10±0.64) cde	(14.31±1.12) cdefg	(19.25±2.24) de	(71.02±2.50) bc
603	(80.38±2.56) a	(3.60±0.78) f	(15.07±1.87) b	(18.31±2.94) ef	(72.42±3.08) a
604	(79.04±2.41) bcd	(4.10±0.56) cde	(14.57±1.39) bcde	(19.24±2.17) de	(71.15±2.52) bc
605	(79.52±1.54) abcd	(3.85±0.53) ef	(14.17±0.93) defg	(18.52±1.59) ef	(71.82±1.75) ab
606	(78.54±1.90) de	(4.05±0.53) de	(14.78±0.96) bcd	(19.69±1.79) cd	(70.60±2.04) cde
607	(77.82±3.09) ef	(4.84±1.32) a	(14.51±1.84) bcdeg	(20.44±3.06) abc	(69.81±3.37) ef
608	(79.76±2.32) abc	(4.03±0.58) de	(14.13±1.08) efg	(18.36±2.33) ef	(72.06±2.61) ab
702	(79.97±2.03) ab	(3.65±0.65) f	(13.79±1.18) g	(17.92±2.08) f	(72.42±2.29) a
CK	(78.75±2.23) cde	(4.14±0.67) cde	(14.43±1.13) cdef	(19.38±2.22) de	(70.91±2.48) bcd

Note: values in the bracket are mean ± standard deviation, and the significant level is 0.05.

clones did not significantly differ from that of clone 603. Therefore, these nine clones were classified as clones with higher yellow/blue axis chromaticity indices.

Difference in ΔE^* values among various *Paulownia* clones

The color differences ΔE^* also significantly differed among the 18 *Paulownia* clones (ANOVA analysis, Table 2). The ΔE^* values ranged from 17.92–21.37, the maximum was 19.22% higher than the minimum, and the CV was between 8.58% and 16.06%. Therefore, the ΔE^* value was considered a more variable parameter, thereby offering a higher possibility for improvement. Compared to CK, 13 *Paulownia* clones had relatively lower ΔE^* values ranging from 0.53% to 7.52%. Duncan's post-hoc test showed that only clone 702 had significantly lower ΔE^* values, which was 7.52% lower than that of CK. The other 6 clones, including 603, 608, 209, 605, 204, and 203, had lower ΔE^* values than that of CK, ranged from 2.40% to 5.49%. However, the ΔE^* values of these 6 clones did not significantly differ from that of clone 702. Therefore, these 7 clones were classified as clones with relatively lower color differences.

Difference in W values among various *Paulownia* clones

W is a particularly important color parameter of *Paulownia* timber. A higher W value indicates better whiteness and higher quality (Zu & Zhou, 1998; Zhai, 2012). One-way ANOVA analysis showed that the W values significantly differed among the 18 *Paulownia* clones (Table 2). The W

values ranged from 68.92 to 72.42, with the maximum value only 5.09% higher than the minimum. Furthermore, a relatively small CV (2.43%–4.82%) was observed. Therefore, *W* was considered as a relatively stable color parameter, and was thereby of lower value for clone selection. Compared to CK, 13 clones had relatively higher *W* values, with *ΔW* ranging from 0.16% to 2.14%. Duncan's post-hoc test showed that clones 603 and 702 had significantly higher *W* values than that of CK (2.14% and 2.13%, respectively). The other 6 clones, including 608, 209, 605, 204, 203, and 101, had slightly higher *W* values than that of CK (*ΔW* ranged from 0.59% to 1.62%), although these did not significantly differ from those of clones 603 and 702. Therefore, these eight clones were considered as clones with a higher degree of whiteness.

Differential analysis of the five color parameters of various *Paulownia* clones determined that clones 702, 605, and 204 had higher *L** and *W* values, and lower *a*, b**, and *ΔE** values, thereby indicating that these clones had superior color properties.

Cluster analysis of wood color parameters of various *Paulownia* clones

Cluster analysis of *L*, a*, b*, ΔE**, and *W* values by using a farthest neighbor algorithm was performed to identify *Paulownia* clones with similar color features. The results showed that the 18 clones included in the present study could be classified into three categories (Figure 2). Class I included clones 102, 201, 205, and 607; class II included 601, 202, 209, 608, 301, 604, 606, 101, and CK; and class III included 204, 605, 702, and 603.

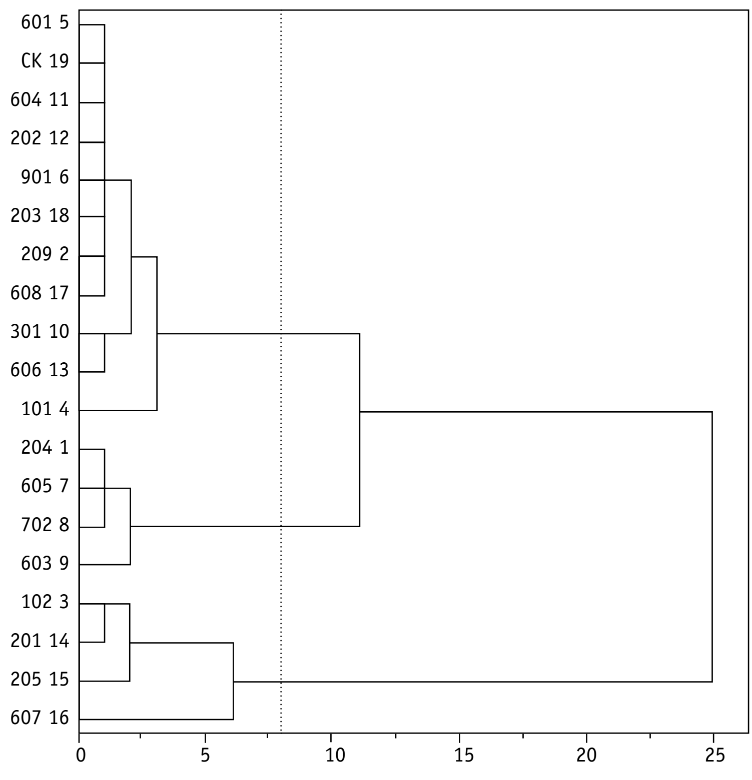

Figure 2. Cluster analysis of wood color parameters of various *Paulownia* clones.

Table 3. Differences in color parameters among the three categories.

Categories	L^*		a^*		b^*		ΔE^*		W	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
I	77.53	77.19~77.92	4.52	4.33~4.84	14.92	14.51~15.69	20.74	20.36~21.37	69.46	68.92~69.89
II	79.15	78.54~79.76	4.13	4.02~4.40	14.31	13.91~14.78	19.00	18.36~19.69	71.35	70.60~72.06
III	79.84	79.51~80.38	3.69	3.60~3.85	14.34	13.79~15.07	18.34	17.92~18.60	72.11	71.77~72.42

The color parameters of the three categories were compared and analyzed, and the results are summarized in Table 3. Category I had the lowest L^* and W and the highest a^*, b^* and ΔE^* values, which suggested relatively poor color characteristics. The values of the color parameters of clones belonging to category II were between those of Categories I and III. In category III, except for clone 603, which had slightly higher b^*, all other clones (including 204, 605, and 702) had comparable values of individual color parameter, higher L^*, greater W, smaller ΔE^*, and higher color indices. Therefore, Category III were described as clones with better color properties, which in turn can be further developed into elite *Paulownia* clones that are suitable for propagation in the study area.

Discussion and Conclusion

L^*, a^*, b^*, ΔE^*, and W of the tested *Paulownia* clones ranged from 77.19 to 80.38, 3.60 to 4.84, 13.79 to 15.69, 17.92 to 21.37, and 68.92 to 72.42, respectively. The observed significant differences in these color parameters may be used as bases for the selection of elite clones with superior color properties.

Differential analysis of color parameters and clustering analysis showed that clones 204, 605, 702, and 603 were elite clones with superior color properties. L^* and W of clones 204, 605, and 703 increased by 0.97%–1.55% and 1.22%–2.13%, respectively, whereas a*, b^*, and ΔE^* of these three clones decreased by 6.94%–11.74%, 0.67%–4.49%, and 4.04%–7.52%, respectively. Interestingly, clone 603 showed a significant increase in L^* and W values (by 2.07% and 2.14%, respectively), a significant decrease in a^* and ΔE^* values (by 13.08% and 5.49%, respectively), and a 4.37% increase in b^*. These results showed that all 4 clones (i.e., 204, 605, 702, and 603) had increased L^* and W and decreased a^* and ΔE^* compared to those of the other clones. In terms of b^*, expect for clone 603, which showed a 4.37% increase, the other clones also had decreased values. Qiu (2013) measured the W values of four different *Paulownia* species and their results showed that *P. kawakamii* T. Ito had the smallest W value (63.89), whereas *P. fortune* showed the highest W value (70.84). In this study, except for *P. fortune*, the W values of *P. tomentosa*, *P. fargesii*, and *P. kawakamii* were all smaller than 67.

The color parameters of other commonly used timbers in China have also been analyzed. Liu (1994) reported that the L^*, a^* and b^* of *Cinnamomum longepaniculatum* (Gamble) N. Chao ex H.W. Li was 70.91, 5.88, 23.74, respectively; *Fraxinus mandshurica* Rupr. was 66.82, 6.65, and 54.15, respectively; and *Pinus koraiensis* Siebold et Zucc. was 71.62, 7.94, 29.22, respectively. Compared to these three species, *Paulownia* showed higher L^* and lower a^* and b^*. Based on the colorimetry study involving 97 wood specimens from French Guiana that was conducted by Nishino et al. (1998), 85 species had $L^* < 70$, whereas 12 species had $L^* > 70$. Among the 97 species, a^* ranged from 4.55 to 19.36, with only three species with $a^* < 5$. B^* ranged from 14.15 to 34.22, with only

3 species with $b^* < 15$. These comparisons indicated that *Paulownia* timber had higher L^* and W, lower a^* and b^*, as well as more stable color differences. These color properties make *Paulownia* timber a suitable material for interior decorations.

Several studies on wood color measurements have been conducted. However, most of the studies focused on the comparison of color parameters among different wood species or various processing methods in one species (Zu & Zhou, 1998; Ru *et al.*, 2007; Zhai, 2012; Chang *et al.*, 2013). For *Paulownia* wood, most studies have focused on the causes and prevention of discoloration, as well as the techniques to correct this negative colorimetric feature (Teischinger *et al.*, 2012; Forsthuber *et al.*, 2013). In the present study, we identified 4 *Paulownia* clones, namely 204, 605, 702, and 603, to have superior color properties. Chang *et al.* (2013) conducted a differential analysis of color differences in four *Paulownia* species. Compared to their results, L^*, a^*, and W obtained in the study were relatively higher, whereas b^* and ΔE^* were relatively lower, which may be attributable to differences in the age of the wood. Because wood color tends to become darker as it ages. In addition, it also should be noted that other parameters such as physical and mechanical properties will require further investigations in order to guide the directional breeding of *Paulownia* clones.

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