Comprehensive Selection of the Wood Properties of *Paulownia* Clones Grown in the Hilly Region of Southern China

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The wood properties of *Paulownia* clones determine their ultimate price and uses. This study selected superior clones with good color and mechanical properties using selection indexes. Variation in 23 5-year-old *Paulownia* clones was analyzed using genetic parameters, correlation analysis, and a comprehensive assessment of two color characteristics [color difference (ΔE) and whiteness (WH)] and six mechanical properties [density (ρ), hardness of the tangential, radial, and end surfaces (H_t, H_r, and H_e), and cleavage strength of the tangential and radial surfaces (q_t, q_r)]. There were significant differences ($p < 0.01$) in each of the eight traits among the 23 clones. There were significant negative phenotypic and genetic correlations between ΔE and WH. The six mechanical properties were significantly positively correlated genetically, showing significant positive phenotypic correlations with each other, except for ρ, H_t, and q_t. With a selection rate of 8.70%, clones MB04 and L01 were selected as superior using the comprehensive selection index. Compared with the control (9501), the genetic gains of clones MB04 and L01 in ΔE, WH, ρ, q_r, q_t, H_e, H_r, and H_t were 0.40, 0.21, 10.32, 12.57, 14.81, 26.05, 28.04, and 6.84%, respectively, and the actual gains were 0.59, 0.31, 17.21, 28.45, 28.09, 34.90, 40.08, and 11.12%.

Keywords: Paulownia clones; Color characterization; Mechanical properties; Phenotypic variation; Genetic variation; Comprehensive selection

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INTRODUCTION

Approximately 82% of the continental biomass and over 50% of the terrestrial biodiversity worldwide are in forest ecosystems (Petit and Hampe 2006; Neale *et al.* 2011; Duan *et al.* 2016). The abundant trait variation of trees enhances their adaptability to various environments and offers the possibility of selecting trees with ideal characteristics (Hoffmann *et al.* 2011; Lopes *et al.* 2015; Matuszewski *et al.* 2015). Most tree characteristics are quantitative traits regulated by multiple genes (Bradshaw *et al.* 2000; Wang *et al.* 2010). In the past, the selection criteria for good trees were primarily growth characteristics, adaptability, and the ability to resist pests and diseases. Although breeding programs need to consider the basic timber properties, these have not received much attention (Huda *et al.* 2014). However, timber quality (color and mechanical properties) directly influences its economic value. To achieve greater economic benefits, the wood color and mechanical properties must be assessed comprehensively.

Paulownia species are very adaptable, extremely fast-growing tree species that are widely cultivated in subtropical and warm temperate regions (Ayrilmis and Kaymakci 2013; Candan *et al.* 2013; Salari *et al.* 2013). They are mainly used for timber and for producing ameliorating microclimates in intercropping systems (Wu *et al.* 2014). *Paulownia* plantations are also used to reduce soil denudation and for tree-crop intercropping patterns and farmland shelter because of their advanced root systems and adaptability to various soil conditions (Smiley 1961; Lucas-Borja *et al.* 2011). *Paulownia* wood is good for fabricating plywood, paper, and furniture because of its velvety texture and excellent grain patterns (Beel *et al.* 2005; Ashori *et al.* 2009). Therefore, *Paulownia* has an important role in easing the imbalance between wood supply and demand. They are fast-growing, broad-leaved species that should be promoted for timber plantations (Wu *et al.* 2014). For many years, *Paulownia* clones were selected using direct selection for a single trait (*e.g.*, growth rate, stem form, wood color, *etc.*) or a single trait permutation selection method (gradually achieving genetic improvement of multiple traits). Few studies have examined the comprehensive improvement of multiple traits (Cotterill and Jackson 1985; Cotterill 1985; Qiu *et al.* 2014; Zhao *et al.* 2017), which greatly reduces the selection effect in multiple trait breeding.

In this study, a comprehensive evaluation of the color characteristics and mechanical properties of 23 *Paulownia* clones was performed. The variance and genetic parameters of eight traits were analyzed, and superior clones with good color and mechanical properties were identified using a comprehensive selection index. The purpose of this research was to select comprehensively of middle-mature forest in terms of wood color and mechanical properties, and to guide the genetic improvement, processing, and utilization of *Paulownia*.

EXPERIMENTAL

General Introduction to the Research Region

The study site was located in Chongyang County, Xianning city, Hubei Province, China (29°33′ N, 114°01′ E), a hilly region at 180 m above sea level with 15 to 25° slopes. The mean annual temperature, precipitation, and daylight hours were 15.8 °C, 1988.5 mm, and 1775 h, respectively. The soil is a yellow-red soil with a frost-free period of 263 days.

One-year-old root piles of *Paulownia* clones with a ground diameter of 3.5 ± 0.5 cm were used for afforestation in the spring of 2008. The density of planting was 4 × 5 m, and each tree was given 3 kg of organic fertilizer as base fertilizer. The 23 *Paulownia* clones used in the experiment were selected out by super seedling selection and seedling stage check, and they were planted according to a completely randomized block design with three blocks, and each block contained randomly plots of the 23 clones. Within each plot, there were six trees of the same clone planted. The control group was clone 9501, a natural hybrid of *Paulownia fortunei* which has been widely planted in China. The experimental forest around the protection tree lines was tended regularly. All of the *Paulownia* clones used in this study were cut down in the spring of 2013, at which time, their average height and diameter at breast height were 8.17 ± 0.75 m and 18.96 ± 1.36 cm, respectively.

Production of Test Pieces

For each clone, three representative trees were sampled for each block. One 8-cm-long disk was cut at 1.36 to 1.44 m above the base of the tree, and three 6-cm-long disks were cut at 1.18 to 1.36 m above the base of the tree. Each disk was marked in four directions, the east, south, west, and north. The sample logs were sawn, and test specimens were made according to Fig. 1. The hardnesses of the end, radial, and tangential surfaces were measured in 36 specimens with end × radial × tangential dimensions of 70 mm× 50 mm× 50 mm. The density and two color traits were measured in the same 36 specimens shaved with end × radial × tangential dimensions of 50 mm× 50 mm× 50 mm. The cleavage strength of the tangential and radial surfaces were determined for 36 specimens each, which measured 50 mm× 20 mm× 20 mm (end × radial × tangential).

Table 1. 23 *Paulownia* Clones Used in this Study

No.	Clone Identity	Clone Source	Female Parent	Male Parent
1	M01	selection of plus tree	*Paulownia tomentosa*	--
2	M02	natural hybrid	*Paulownia tomentosa*	**
3	B01	natural hybrid	*Paulownia fortunei*	**
4	B02	natural hybrid	*Paulownia fortunei*	**
5	B03	natural hybrid	*Paulownia fortunei*	**
6	B05	natural hybrid	*Paulownia fortunei*	**
7	B07	natural hybrid	*Paulownia fortunei*	**
8	B09	natural hybrid	*Paulownia fortunei*	**
9	L01	selection of plus tree	*Paulownia elongata*	--
10	C01	selection of plus tree	*Paulownia fargesii*	--
11	MB01	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
12	MB02	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
13	MB04	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
14	MB05	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
15	MB06	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
16	MB07	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
17	MB08	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
18	MB10	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
19	MB11	artificial hybrid	*Paulownia tomentosa*	*Paulownia fortunei*
20	BM01	artificial hybrid	*Paulownia fortunei*	*Paulownia tomentosa*
21	BM02	artificial hybrid	*Paulownia fortunei*	*Paulownia tomentosa*
22	BL01	artificial hybrid	*Paulownia fortunei*	*Paulownia elongata*
23	9501（CK）	natural hybrid	*Paulownia fortunei*	**
Note: --, No male parent (asexual propagation); **, Male parent Unknown				

Research Methods

The total color difference and whiteness indices were measured on the radial surfaces of dry specimens using a Konica Minolta CR-400 with a D65 standard source. The specimen density index was measured the GB/T 1933-2009 (2009) standard. The specimens were kept in an oven at 60 °C for 4 h and then maintained at 103 ± 2 °C until a constant weight was reached; this was deemed the dry weight. The mass (m) was measured with an AL204 electronic balance from Mettler Toledo (precision 0.0001 g). The length (l), width (w), and height (h) were measured with digital vernier calipers (precision 0.01 mm), and the full dry densities were calculated using the formula $\rho = m/(l \times w \times h)$.

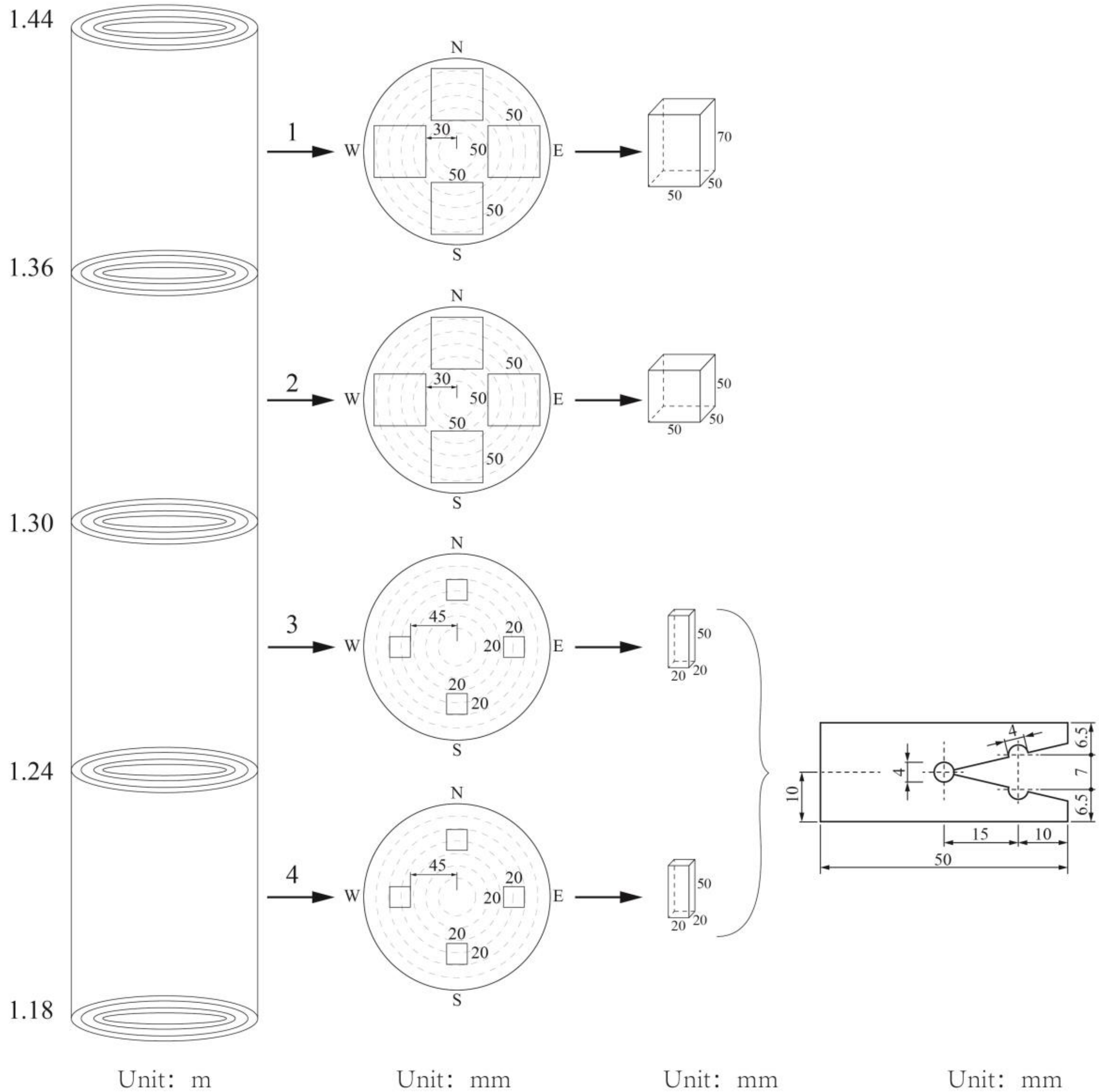

Fig. 1. Sampling methods for discs and logs and test samples for the color characteristics and mechanical properties of wood. Test samples for the (1) hardness, (2) density and color, (3) cleavage strength of tangential surfaces, and (4) cleavage strength of radial surfaces

The cleavage strength could only be measured for one surface per specimen because this requires making a wedge incision. The cleavage strengths of radial and tangential specimens were measured according to the GB/T 1942-2009 (2009) standard. First, the moisture contents of the specimens were adjusted to 12%. After measuring the width (b) of surfaces used for the wedge incisions, the specimens were loaded on the mechanical test machine and destroyed within 0.2 to 0.5 min by increasing the load at a uniform rate; the breaking load was labeled as P_{max}. The cleavage strength (q) at 12% moisture content was calculated using the formula $q = P_{max}/b$.

The hardness index was measured according to GB/T 1941-2009 (2009). The moisture content was the same as in the cleavage strength test. After the specimen was loaded on the mechanical test machine, the steel head was pressed into the test face to a depth of 5.64 mm at a uniform speed of 3 to 6 mm/min; the load at this point was denoted H_w. The radial, tangential, and end faces of each specimen were tested twice, and the average was used as hardness of each surface. The hardness (H) at 12% moisture content was calculated using the formula $H = H_w$.

Statistical Analysis

Given a *Paulownia* clones available for testing with b blocks, each consisting of n plots planted, and using the value of a single observation as the statistical unit, the linear analysis of variance (ANOVA) model for this analysis was $x_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ijk} + e_{ijk}$, where μ is the population mean, α_i is the clone effect, β_j is the block effect, $\alpha\beta_{ijk}$ is the interaction effect between clone and block, and e_{ijk} is the random error (Pâques *et al.* 2013). The formula for clonal repeatability is $H^2 = \frac{\sigma_a^2}{\sigma_a^2 + \sigma_{ab}^2/\mathrm{b} + \sigma_e^2/nb}$, where σ_a^2 is the clonal variance component, σ_{ab}^2 is the variance component of the interaction effect between clone and block, and σ_e^2 is the variance component of the random error (Xu 2006). The phenotypic variation coefficient is $PCV = \frac{S}{\overline{x}} \times 100\%$, and the genetic variation coefficient is $GCV = \frac{\sqrt{\sigma_a^2}}{\overline{x}} \times 100\%$, where S and $\overline{x}$ are the phenotypic standard deviation and the mean of a trait, respectively (Lai *et al.* 2014). The phenotype correlation coefficient is $r_{p12} = \frac{Cov_{p12}}{\sqrt{\sigma_{p1}^2 \sigma_{p2}^2}}$, and the genetic correlation coefficient is $r_{g12} = \frac{Cov_{g12}}{\sqrt{\sigma_{g1}^2 \sigma_{g2}^2}}$, where σ_{p1}^2 and σ_{p2}^2 are the phenotypic variances of the two traits, σ_{g1}^2 and σ_{g2}^2 are the genetic variances of the two traits, and Cov_{p12} and Cov_{g12} are the phenotypic and genetic covariances of the two traits (Xu 2006). The genetic gain is $\Delta G = (H^2 M/\overline{x}) \times 100\%$, and the actual gain is $G = (M/\overline{x}) \times 100\%$, where M is the difference between the means of a trait in the selected clonal population and the control (Zhao 2002).

The selection for multiple traits in the 23 *Paulownia* clones was assessed using the Smith–Hazel selection index (Cotterill and Dean 1990), which estimates the economic weight of each trait by using an equal weight method (W). Thus, W is calculated as $W_i = 1/\sigma_i$, where σ_i is the phenotypic standard deviation of each trait (Cotterill and Jackson 1985). Depending on the breeding objectives, to adjust for the appropriate multiple (Zhao *et al.* 2015), the selection index is calculated as $I = b_1x_1 + b_2x_2 + \ldots b_nx_n$, where $b = P^{-1}GW$, and b_i, x_i, and σ_i are the index coefficient, mean, and phenotypic standard deviation of each trait, respectively, P and G are the phenotypic and genetic variance covariance matrix, respectively, and W is the economic weight vector of each trait (Wang *et al.* 2012).

RESULTS AND DISCUSSION

Difference Analysis and Genetic Parameter Estimation

Variation among clones is the basis of clonal breeding. The size of the variation coefficient not only reflects the degree of variation within a group but also decides the selection space (Zhao *et al.* 2012; Du *et al.* 2015). The coefficient of genetic variation reflects the degree of variation in traits caused by genetic factors; a large value indicates that the trait has a relatively large potential for improvement among different clones (Wang *et al.* 2012). Table 2 shows the ANOVA and genetic parameter estimation for the eight traits studied. The F values of the eight traits ranged from 3.3037 to 22.0960. The results show that these traits were weakly affected by the external environment, and there were real genetic differences. Therefore, large gains can be obtained by selecting clones (Huang *et al.* 2005). The genetic and phenotypic variation coefficients (*GCV* and *PCV*) of cleavage strength were both in the order $q_t > q_r$; the *PCV* of hardness was in the order $H_t > H_r > H_e$; and the *GCV* of hardness was in the order $H_r > H_t > H_e$. The *GCV* and *PCV* of cleavage strength and hardness were the largest, followed by ρ and ΔE, and then by *WH*. The change in *GCV* ranged from 5.5474 to 50.2532%, and the change in *PCV* ranged from 3.5141 to 21.9049%. The results indicated that was easiest to select clones with a high *q* and *H*, and then ρ, ΔE, and *WH*.

Table 2. Analysis of Variance and Genetic Parameter Estimation

Traits	ΔE	*WH*	ρ	Cleavage strength		Hardness		
				q_r	q_t	H_e	H_r	H_t
Means	19.1857	71.1203	0.2509	13.3281	13.5747	2281.50	1012.75	1268.97
F-values of the clones	3.5899†	3.3037†	22.0960†	10.2896†	11.0161†	16.0004†	13.7519†	8.9550†
Variance component of the clones	13.2593	15.4969	0.0029	26.9736	34.5322	712369	259020	340638
Interaction variance component	4.4080	5.2287	0.0011	15.0569	16.3204	180544	77776	130997
Error	3.6935	4.6908	0.0001	2.6214	3.1347	44521	18835	38038
Repeatability of clones	0.6676	0.6626	0.5996	0.4418	0.5274	0.7466	0.6997	0.6154
Phenotypic variation coefficient (PCV) (%)	11.7476	3.5141	8.8721	18.9834	20.2686	15.0735	21.2554	21.9049
Genetic variation coefficient (GCV) (%)	19.0353	5.5474	21.4604	38.9673	43.2896	36.9940	50.2532	45.9932

Note: ΔE, total color difference; *WH*, whiteness; ρ, full dry density; q_r and q_t, cleavage strengths of the radial and tangential surfaces; H_e, H_r, and H_t, hardness of the end, radial, and tangential surfaces;
†, the trait F-values of the clones are significant at $P < 0.01$.

Table 3 shows Duncan's multiple comparisons of the eight traits among the 23 *Paulownia* clones.

Table 3. Duncan's Multiple Comparison of the Color and Mechanical Properties of the 23 *Paulownia* Clones

Clone \ Traits	ΔE	WH	ρ	Cleavage strength		Hardness		
				q_r	q_t	H_e	H_r	H_t
M01	19.10 ± 2.03 bcd	71.35 ± 2.22 abc	0.2206 ± 0.0077 l	11.83 ± 1.37 ghij	11.54 ± 1.88 cd	1961.23 ± 146.71 ij	785.58 ± 85.32 i	974.18 ± 159.43 j
M02	21.41 ± 1.79 a	68.56 ± 2.17 e	0.2346 ± 0.0143 jk	12.21 ± 2.34 fghi	12.79 ± 2.80 bc	1880.09 ± 225.51 j	853.98 ± 114.75 hi	1065.91 ± 84.01 ij
B01	19.22 ± 1.21 bcd	71.13 ± 1.24 abc	0.2621 ± 0.0104 cd	14.79 ± 1.94 abc	14.79 ± 1.94 a	2294.83 ± 176.86 defg	1062.74 ± 173.24 bcde	1279.69 ± 86.30 defg
B02	18.76 ± 2.01 bcd	71.46 ± 2.42 abc	0.2544 ± 0.0315 defg	15.04 ± 2.04 ab	15.21 ± 1.98 a	2381.77 ± 224.89 cdef	1142.59 ± 105.49 bc	1437.10 ± 176.75 bcd
B03	18.22 ± 1.94 cd	72.21 ± 2.30 ab	0.2463 ± 0.0115 ghi	11.50 ± 1.75 hij	10.79 ± 0.92 de	2118.83 ± 193.20 ghi	925.45 ± 925.45 fgh	1099.79 ± 176.11 ghij
B05	21.33 ± 2.08 a	68.91 ± 2.17 de	0.2765 ± 0.0089 ab	13.38 ± 3.00 cdef	14.08 ± 3.01 ab	2584.75 ± 229.59 b	1319.37 ± 206.78 a	1624.29 ± 210.63 a
B07	19.04 ± 1.66 bcd	71.11 ± 1.78 abc	0.2417 ± 0.0319 hij	11.13 ± 3.61 ij	10.67 ± 2.72 de	2192.44 ± 420.99 fgh	877.73 ± 198.35 ghi	1112.22 ± 209.62 fghij
B09	18.91 ± 2.64 bcd	71.41 ± 2.94 abc	0.2553 ± 0.0238 defg	12.46 ± 3.83 fghi	13.88 ± 4.47 bcde	2286.03 ± 260.90 defg	885.55 ± 190.45 ghi	1219.47 ± 164.10 efghi
L01	18.97 ± 1.03 bcd	71.40 ± 1.08 abc	0.2674 ± 0.0150 bc	14.29 ± 1.42 bcd	15.00 ± 1.80 a	2561.43 ± 229.01 bc	1077.72 ± 165.22 bcde	1236.42 ± 173.18 efghi
C01	19.07 ± 0.95 bcd	71.22 ± 1.02 abc	0.2278 ± 0.0147 kl	13.38 ± 2.00 cdef	13.83 ± 1.79 ab	1988.98 ± 229.27 ij	846.37 ± 171.75 hi	1080.33 ± 233.66 hij
MB01	18.62 ± 1.62 cd	71.59 ± 1.85 abc	0.2562 ± 0.0135 defg	16.00 ± 2.24 a	15.33 ± 1.93 a	2544.31 ± 173.61 bc	1060.68 ± 70.82 bcde	1311.74 ± 81.11 cde
MB02	18.34 ± 3.28 cd	72.30 ± 3.53 ab	0.2514 ± 0.0126 efgh	13.67 ± 1.81 bcdef	14.08 ± 2.30 ab	2374.38 ± 192.82 cdef	1088.03 ± 101.16 bcd	1219.49 ± 107.51 efghi
MB04	17.99 ± 1.36 d	72.27 ± 1.97 ab	0.2845 ± 0.0186 a	14.46 ± 2.52 bcd	14.79 ± 2.01 a	2877.96 ± 269.50 a	1307.21 ± 188.66 a	1579.42 ± 191.70 ab
MB05	18.44 ± 1.61 cd	71.91 ± 1.87 ab	0.2612 ± 0.0099 cde	10.58 ± 1.58 j	9.58 ± 1.08 e	2409.54 ± 178.54 bcde	1173.06 ± 159.75 b	1463.30 ± 265.96 abc
MB06	20.20 ± 2.29 abc	70.18 ± 2.77 bcde	0.2466 ± 0.0136 ghi	14.54 ± 2.07 abcd	14.92 ± 3.29 a	2114.96 ± 313.86 ghi	888.38 ± 172.28 ghi	1132.59 ± 243.78 efghij
MB07	19.23 ± 3.00 bcd	71.05 ± 3.39 abcd	0.2604 ± 0.0148 cde	13.38 ± 1.38 cdef	13.67 ± 1.44 ab	2318.31 ± 262.95 def	1062.96 ± 164.55 bcde	1420.56 ± 386.60 bcd
MB08	17.55 ± 2.23 d	72.93 ± 2.55 a	0.2505 ± 0.0293 efgh	14.88 ± 2.21 abc	14.92 ± 2.90 a	2019.01 ± 424.31 hij	955.28 ± 285.18 efgh	1417.87 ± 601.44 bcd
MB10	19.37 ± 1.69 bcd	71.05 ± 1.84 abcd	0.2644 ± 0.0230 cd	14.00 ± 1.26 bcde	14.21 ± 1.25 ab	2462.14 ± 299.70 bcd	1114.09 ± 274.67 bcd	1421.92 ± 340.88 bcd
MB11	19.37 ± 2.22 bcd	70.85 ± 2.38 abcd	0.2428 ± 0.0110 hij	12.75 ± 1.14 efgh	12.67 ± 1.19 bc	2242.36 ± 256.18 efg	949.88 ± 94.32 efgh	1151.41 ± 174.20 efghij
BM01	19.45 ± 1.64 bcd	70.89 ± 1.69 abcd	0.2495 ± 0.0120 fgh	13.63 ± 2.64 bcdef	14.00 ± 1.82 ab	2193.45 ± 296.71 fgh	1003.33 ± 101.14 defg	1210.22 ± 111.78 efghi
BM02	17.90 ± 2.37 d	72.54 ± 2.59 ab	0.2584 ± 0.0177 cdef	15.00 ± 1.60 ab	14.92 ± 1.44 a	2434.77 ± 370.99 bcde	1057.98 ± 133.76 bcde	1299.31 ± 238.34 cdef
BL01	20.70 ± 2.98 ab	69.49 ± 3.21 cde	0.2385 ± 0.0145 ij	13.15 ± 1.87 defg	14.58 ± 2.44 a	2295.47 ± 268.81 defg	1040.77 ± 217.42 cdef	1215.65 ± 217.71 efghi
9501(CK)	18.59 ± 1.29 cd	71.61 ± 1.37 abc	0.2328 ± 0.0063 jk	10.58 ± 2.31 j	11.08 ± 2.77 de	1923.54 ± 121.24 j	786.57 ± 124.45 i	1266.84 ± 146.54 defgh

Note:
The abbreviations for the trait names are the same as in Table 2;
The values in brackets are the mean ± standard deviation, and the different letters indicate significant differences at the 0.05 level according to Duncan's multiple comparison.

The ΔE of clones MB08, BM02, MB04, B03, MB02, and MB05 were lower than that of the control. The *WH* of clones MB08, BM02, MB02, MB04, B03, and MB05 were higher than that of the control. The ρ values of the other clones were higher than the control, except for C01 and M01. More than half of the clones had significantly higher q and H values than the control, except for the value of H_t.

Correlational Analysis

Table 4 shows the correlation coefficients between the phenotypic and genetic mechanical properties for the 23 clones. The phenotypic and genetic correlation coefficients of ΔE and *WH* were -0.9751 and -0.9987, respectively, and both were significant. The six mechanical traits showed strong significant ($P < 0.01$) positive genetic intercorrelations. There were also significant ($P < 0.01$) positive phenotypic correlations between members of each pair, except for q_t, H_t, and ρ. The phenotypic correlation coefficients between color and the mechanical traits were not significantly different from each other, except for q_r, while the genetic correlation coefficients between color and the mechanical traits differed significantly, except for H_r and H_t. The correlation coefficients between tree traits can provide a theoretical reference for a genetic improvement strategy for trees and is important in tree breeding (He *et al.* 2002). For the eight traits we studied, the correlation coefficients between members of each pair varied; phenotypic and genetic correlation coefficients differed not only in magnitude but also in sign (positive and negative). The genetic correlation coefficients for H_e, H_r, and H_t between each pair were 0.9422, 0.8684, and 0.6947. Therefore, the hardness of wood can be expressed by a single one of these to save time and costs. Similarly, cleavage strength can be expressed using q_r or q_t.

Table 4. Correlation Coefficients Between the Color and Mechanical Properties of the Clones

Correlation Coefficients	ΔE	*WH*	ρ	q_r	q_t	H_e	H_r	H_t
ΔE		–0.9751†	0.0832	0.1498†	–0.0151	0.0782	–0.0243	0.0936
WH	–0.9987†		0.0886	0.1511†	–0.0112	0.0803	–0.0224	0.0926
ρ	–0.2549†	0.2795†		0.1448*	0.1027	0.5763†	0.5889†	0.4409†
q_r	–0.2524†	0.3147†	0.5032†		0.4078†	0.1543†	0.1414*	0.1373*
q_t	0.1926†	–0.1282*	0.3262†	0.9947†		0.1302*	0.1619†	0.1058
H_e	–0.1322*	0.1457*	0.9861†	0.5902†	0.4011†		0.6072†	0.3323†
H_r	0.0986	–0.0698	0.9879†	0.6149†	0.4415†	0.9422†		0.5110†
H_t	–0.0830	0.0833	0.9872†	0.4543†	0.2869†	0.6947†	0.8684†	

Notes:
Phenotypic (genetic) correlation coefficients are in the upper (lower) triangle;
* and † indicate significant correlations at the 5% and 1% levels, respectively.

Multi-Trait Index Selection

The economic weights of the eight traits shown in Table 5 were determined by the equal weight method. The economic weights of ΔE and *WH* were –0.4437 and 0.4001, respectively. ρ had the highest economic weight (44.9172), followed by q_r (0.3952) and q_t (0.3635). H_e, H_r, and H_t had the lowest economic weights, 0.0029, 0.0046, and 0.0036, respectively. Based on the correlations with the other traits, the unconstrained and equal weight methods were used to build multiple trait exponential equations using equal weights of the traits, emphasizing color traits, and emphasizing mechanical properties, respectively. Table 6 shows the combined selection progress of the equations and genetic progress on the traits. Using the eight traits as the evaluation indices, the 23 clones were comprehensively evaluated using the exponential equations I_1, I_2, and I_3, respectively. The comprehensive selection values were 3.2477, 4.7385, and 9.1449, respectively, and the genetic progress of the eight traits was positive, except ΔE.

Table 5. Economic Weights of the Eight Traits

Selection indices	ΔE	WH	ρ	q_r	q_t	H_e	H_r	H_t
I_1	–0.4437	0.4001	44.9172	0.3952	0.3635	0.0029	0.0046	0.0036
I_2	–1.3311	1.2003	44.9172	0.3952	0.3635	0.0029	0.0046	0.0036
I_3	–0.4437	0.4001	134.7517	1.1857	1.0904	0.0087	0.0139	0.0108

According to the 21.7% selection ratio, clones MB04, B05, MB02, L01, and B02 were selected as excellent clones using equation I_1; clones MB04, MB02, BM02, L01, and MB05 were selected using equation I_2; and clones MB04, B05, B02, L01, and MB10 were selected using equation I_3. All of the equations selected clones MB04 and L01, indicating that clones MB04 and L01 were excellent clones, with good color and mechanical properties.

Table 7 shows the mean value of each trait for the two selected clones (MB04 and L01) under a selection ratio of 8.70%. Compared with the control, the total color difference and whiteness of clone L01 were slightly worse, and all of the other traits were improved to some extent, which might be related to the fact that clone L01 was rooted in *Paulownia elongata*, while clones MB04 and 9501 were both rooted in *Paulownia fortunei*, and the wood color index of *Paulownia fortunei* is better than that of *Paulownia elongata* (Chang *et al.* 2013). The increase in the six mechanical traits was large and ranged from 11.14% to 51.60%, followed by values for ΔE and WH, which were increased by 0.61% and 0.31%, respectively. The genetic and actual gains of the selected population were calculated by comparing the mean values of the traits of the selected population with those of the control; the results are shown in Figure 2. The actual gains of H_r, H_e, and q_r of the selected population were the highest, at 40.08, 34.90, and 28.45%, respectively, followed by q_t (28.09%), ρ (17.21%), and H_t (11.12%), and the lowest actual gains were in ΔE (0.59%) and WH (0.31%). The highest genetic gains for the selected population were in H_r (28.04%) and H_e (26.05%), followed by q_t (14.81%), q_r (12.57%), ρ (10.32%), H_t (6.84%), ΔE (0.40%), and WH (0.21%) (Fig. 2).

A successful breeding program should involve various traits (Sun *et al.* 2005), but trait selection (quantity and type) directly affects the precision of selective breeding. The more traits are selected and the characteristic information represented is comprehensive but may not be able to select out the ideal clones, the fewer traits are selected and it may be easy to choose, but its representative's information may be incomplete (Feng *et al.* 2017). Therefore, different combinations of selected traits should be developed according to specific breeding objectives.

Table 6. Combined Selection and Genetic Progress on the Traits

No.	The Multiple Traits Exponential Equations	Combined Selection Progress	Genetic Progress							
		ΔH	*ΔE*	*WH*	*ρ*	q_r	q_t	H_e	H_r	H_t
I_1	$1.9623x_1 + 2.3926x_2 + 20.9507x_3 – 0.1998x_4 + 0.5407x_5 + 0.0012x_6 + 0.0122x_7 – 0.0006x_8$	3.2477	–0.4720	0.5927	0.0112	1.0014	0.7929	208.93	119.99	125.28
I_2	$2.8968x_1 + 4.2996x_2 + 45.2920x_3 – 0.3666x_4 + 0.4803x_5 + 0.0004x_6 + 0.0132x_7 – 0.0028x_8$	4.7385	–1.0481	1.2127	0.0085	0.7857	0.3803	148.86	70.33	82.87
I_2	$4.9523x_1 + 5.2708x_2 + 38.5109x_3 – 0.4327x_4 + 1.6825x_5 + 0.0045x_6 + 0.0355x_7 + 0.0005x_8$	9.1449	–0.1274	0.2136	0.0115	1.0153	0.9293	219.67	134.02	135.02

This study analyzed variation in two color characteristics (ΔE and WH) and six mechanical properties (ρ, H_t, H_r, H_e, q_t, and q_r) in 23 5-year-old Paulownia clones using genetic parameter evaluation, correlation analysis, and comprehensive assessment. Ultimately, clones MB04 and L01 were selected as superior using the comprehensive selection index under a selection rate of 8.70%. The actual and genetic gains of the selected group were improved compared with the control.

Table 7. Means of the Eight Traits of the Three *Paulownia* Clones

Clones	ΔE	WH	ρ	q_r	q_t	H_e	H_r	H_t
MB04	17.9867	72.2686	0.2845	14.4583	14.7917	2877.96	1307.21	1579.42
L01	18.9675	71.3976	0.2674	14.2917	15.0000	2561.43	1077.72	1236.43
9501(CK)	18.5912	71.6095	0.2328	10.5833	11.0833	1923.54	786.57	1266.84

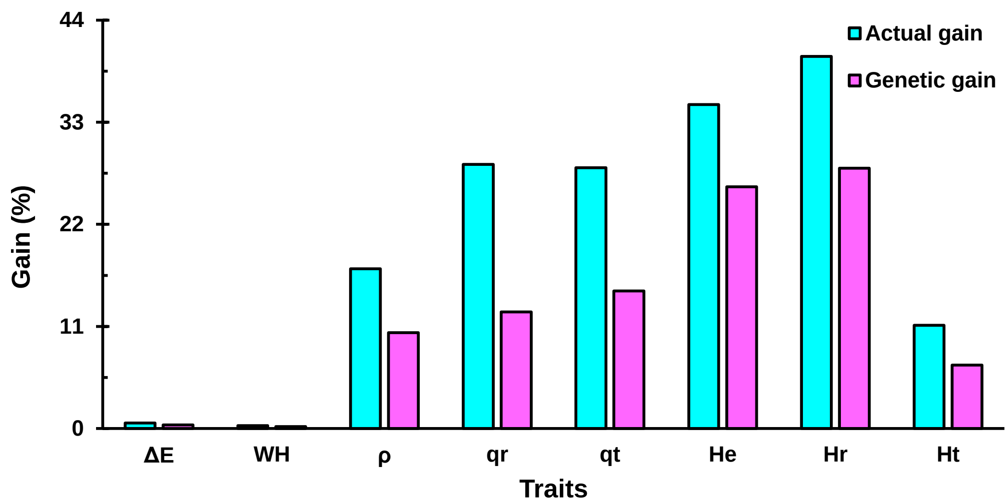

Fig. 2. Genetic and actual gains of the traits at a selection ratio of 8.70%

CONCLUSIONS

1. With a selection rate of 8.70%, clones MB04 and L01 were selected as superior clones using the comprehensive selection index among the 23 *Paulownia* clones. Compared with the control, the genetic gains of the two clones MB04 and L01 in ΔE, WH, ρ, q_r, q_t, H_e, H_r, and H_t were 0.40, 0.21, 10.32, 12.57, 14.81, 26.05, 28.04, and 6.84%, respectively, and the actual gains were 0.59, 0.31, 17.21, 28.45, 28.09, 34.90, 40.08, and 11.12%.
2. Abundant variation was found in the eight traits among the 23 *Paulownia* clones; the phenotypic variation coefficients all exceeded 11.75%, except for WH and ρ, while the genetic variation coefficients exceeded 19.04%, except for WH.
3. The repeatabilities of all eight traits of the 23 *Paulownia* clones were high, and ranged from 0.4418 to 0.7466.
4. The phenotypic and genetic correlations of H_e, H_r, and H_t showed strong significant ($p < 0.01$) positive, Therefore, the hardness of wood can be expressed by a single one of

these to save time and costs. Similarly, cleavage strength can be expressed using q_r or q_t.

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