CONTROL OF WOOD PROPERTIES, DRYING AND WORKABILITY OF WOOD FROM NINE 8-YEAR-OLD CLONES OF *SWIETENIA MACROPHYLLA* KING GROWN IN COSTA RICA

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Swietenia macrophylla is a wood of high commercial value and is planted in reforestation programmes in tropical areas using clones. The present study aimed to evaluate tree growth, physical and mechanical properties, wood colour, lumber quality during sawing and drying, and workability properties, and to establish a selection ranking of nine clones at eight years of age. The results showed that diameter, height and heartwood showed good development and that clones C1, C2, and C207 were the best clones. An unfavourable aspect of the clones evaluated was that the wood presented a lighter colour (higher lightness, lower redness, and higher yellowness) than wood from a natural forest. However, if considering an equilibrium between growing parameters and wood properties, the clone C115 presented important potential for planting in a fast-growth plantation. In relation to the quality of wood after sawing and drying, it was not possible to observe a clear trend in wood quality, which was probably influenced by the early age and did not express the genetic effect of each clone.

Keywords: mahogany, wood properties, breeding, native tree species, decorative wood

INTRODUCTION

Swietenia macrophylla King, with many popular or commercial names, such as mahogany, caoba, palo santo, and others, is a most important tropical wood with high demand in countries where it grows naturally and on international markets.[1] This wood is durable, has an excellent aesthetic quality, and has good workability properties.[2] The wood is used in a wide variety of products, including the manufacture of furniture.[3] Another important aspect of the species is that it grows naturally in Mexico, passes through Central America, and ends up in the Amazon regions of Brazil.[1]

This species began to be exploited in the Neotropical forest with the arrival of the Europeans,[4] and was mainly used for construction, shipbuilding, and furniture.[5] Since that time, it has been widely traded, with high demand on international markets.[4]

Because of this, in addition to the reduced status of its populations, *S. macrophylla* was proposed and included in Appendix II of the Convention on International Trade in Endangered Species (CITES) in 1994,[6] where it is characterised by strictly controlled trade.

Due to its commercial importance, *S. macrophylla* is planted in fast-growth plantations, and it has been observed that it can develop good growth in diameter. The commercial plantations of this species were established not only in the area of natural growth in America, but also in other tropical regions of Asia, Oceania, and Africa.[3] The establishment and management conditions of *S. macrophylla* in plantations were extensively detailed by Krisnawati *et al.*[1] and Pérez.[7] These authors emphasise that the species' rotational period has a range of 20 to 60 years.

The silviculture of species used in commercial reforestation has changed in recent years.[8] Fast-growth plantation concepts have been established, where the rotation period in tropical regions has been mentioned as being less than 25 years.[9] The decrease in this period has occurred due to the improvement of seedling

reproduction techniques, establishment, genetic improvement,[10] and intensive silviculture,[11] as well as increased control or monitoring of growth.[12] The problem with *Meliceae* species in plantations is that they are quickly attacked by the shoot borer *Hypsipyla grandella*, which alters the stem shape of the trees.[1,7] In the case of genetic improvement, it is noted that the use of clones in hardwood species can produce genetic gains between 25% and 50%,[13] based on increasing the production of plantations with trees of adequate development in diameter, tree quality, and high-quality wood.[14] *S. macrophylla* is a species that responds very well to a strict selection of superior or plus trees,[15] and excellent results have been recorded in different clone trials.[16] However, despite these advantages, the genetic improvement of this species is limited, and its improvement is concentrated on trees with good shape, good resistance to the shoot borer attack of *H. grandella* and adequate growth in diameter.[7]

S. macrophylla was introduced into reforestation programmes for sawlog production or the recovery of abandoned sites in Costa Rica.[17] Recently, a series of trials of different clones have been conducted to evaluate their growth, productivity, and even the costs associated with reforestation with this species.[18-20] In the studies by Chinchilla *et al.*[18-19] and Corea-Arias,[20] it was indicated that emphasis should be placed on silvicultural activities that improve the shape of the stem and the quantity of possible logs that can be obtained from the tree, since the species at very low heights loses the apex by the attack of the shoot borer *H. grandella*. In addition, logs from forest plantation trees show good quality for sawmilling, as well as fast drying and good workability, but some disadvantages were found, such as low gravity specifications, light wood tone, and the presence of warps during the sawing and drying processes.[21] Then, these disadvantages cause low economic benefit for *S. macrophylla* planted in fast-growth condition plantations or low economic productivity.[20]

One aspect to note about these studies is that they are mainly focused on the analysis of the morphological properties of the trees, and wood properties are poorly studied. Nunes *et al.*[22] and Makouanzi *et al.*[23] mention the importance of the physical and chemical properties of wood in genetic improvement, indicating that they present high genetic control that should be used in the selection of the best genotypes as a whole growth trait. Gion *et al.*[24] point out that the physical properties of wood are often determined by a single biosynthetic pathway, little influenced by the environment. Thus, wood properties would show greater genetic control than growth traits, because the latter are more influenced by the environment.[24] The importance of wood properties is high; for example, an adequate specific gravity (SG) allows influencing many other wood properties due to the fact that this physical characteristic is associated with many other properties, such as mechanical properties. Other properties that could be inferred from genetic improvement are: (i) an increase in the amount of heartwood (diameter and percentage); (ii) it allows a greater economic benefit; (iii) having logs with a low presence of warps during sawing or drying may increase the set-record of sawlogs; (iv) it allows greater productivity of plantations; and (v) without doubt, the light colour of plantation wood is key for the traditional market of *S. macrophylla* wood, which is focused on a reddish colour and this colour is not present in wood from plantation trees.

Studies of wood from plantations are extensive in *S. macrophylla*; these contemplate chemical, physical, and mechanical wood characterisations;[25-28] variation in heartwood, bark, sapwood, and SG with tree height;[29-31] differences in bending (mechanical properties) and SG between pure and mixed wood plantations and wood from natural forest trees;[32-34] effect of growth rate on SG;[35] the effect of age on SG;[36-37] and its behaviour in the sawing and drying processes.[38]

Regarding the analysis of genetic aspects of wood properties, studies are limited.[16,39] In the Philippines, Abarquez *et al.*,[39] besides examining some genetic variation in growth and form traits of progenies from 73 families of six plantation seed sources at 50 months old, examined specific gravity (SG) and heritability. Sudrajat *et al.*[16] analysed the genetic variation of growth and wood quality traits in 96 families, originating from seven populations (landraces) on Java Island. They planted a progeny test in Indonesia and found that the family heritabilities for all growth and wood quality traits were categorised as high. Besides, the same authors found that the selection simulation showed that the selection percentage of 44.68% (45 best families) gave the optimum genetic gain based on growth and wood quality traits. Finally, Chudnoff and Geary[40] found that different progeny was not significant in a SG in trees of 7-8 years old.

Although there are studies related to the properties of *S. macrophylla*, the information available on the properties and behaviour in industrial processes is scarce, which restricts the use of wood. Thus, it is necessary to generate knowledge about the performance of *S. macrophylla* clones in plantations established with cloned trees. Given this context, the objective of this study is to evaluate and determine the heritability and establish a selection ranking of nine clones of *S. macrophylla* at an age of eight years, growing in the Atlantic zone of Costa Rica, considering the parameters of tree growth (diameter and total height), heartwood and bark percentage, physical and mechanical properties, wood colour, lumber quality during sawing and drying, and workability properties. The knowledge of these variables will enable the genetic improvement programme of this important wood species in the country to be fully optimised.

EXPERIMENTAL

Study site

The plantation with the different clones of *S. macrophylla* is located in Sarapiquí, in the Heredia province of Costa Rica (10° 18' 56.5" N and -83° 55' 13.9" W) (Fig. 1a). This region has a climate with a life zone of very humid tropical forest, in addition to an altitude of 68 m.a.s.l., a mean temperature of 20-30 °C and precipitation ranging between 4000-5000 mm, respectively. The site has a slight slope (0% to 8%), and the soil type is of the inceptisol order, characterised by an acid pH and high organic matter content.

Description and establishment of the trial

At the time of the wood properties evaluation, the plantation was 8 years old, with a density of 234 trees per hectare. The initial establishment was planted with clones from Bolivia and Costa Rica from a collection of 308 genotypes of *S. macrophylla*, which came from a large number of trees in those two countries. In the trial, 26 clones were planted with 9 replicates per clone (Fig. 1b). A zigzag planting design was used with a tree spacing of 3 m between rows and 3 m between trees.

Trial management

At the time of establishment, a granular fertiliser was applied at a rate of 10 grams per tree, with equal concentrations of nitrogen, phosphorus, and potassium. At 10 and 18 months after establishment, 30 grams per tree of fertiliser were applied at a concentration of 10-30-10 nitrogen, phosphorus, and potassium, respectively. At the ages of 10 and 24 months, weed control was applied and herbicide was applied, at the latter age. At the age of 5 years, thinning was carried out at an intensity of 50%. In year 1, there was an attack of *Hypsipyla grandella*, where the borer was manually eliminated and pruning was done to establish a strong trunk, accompanied by the application of Cypermethrin (a pyrethroid insecticide) in order to control the different pests that could occur.

Clone selection

Of the 26 genotypes established in the plantation, only nine had a diameter greater than 10 cm to carry out the study of wood properties. Specimen dimensions for mechanical properties are possible to extract from a log with a diameter of 10 cm, and then clones with this dimension in diameter are selected. This condition is necessary to obtain logs that can be sawn using traditional methods for processing small-diameter logs in Costa Rica.[41] In addition, other dasometric variables, such as diameter, height, trunk quality, and resistance to pests and diseases, all show appropriate values.

Clone sampling and tree sampling

Two trees were selected from the 9 clones, for a total of 18 individuals according to the method proposed by Moya and Muñoz.[28] In each tree sampled, the diameter at breast height (DBH), the total height (HT), and the north position of the tree were measured. In each tree, cross-sections of 3 cm thick were cut at the DBH (Fig. 1c), and 2-3 logs of 1.25 in length were extracted (Fig. 1d) – one between the base of the tree and the DBH, and then other logs until reaching 10 cm in diameter.[28] The cross-sections were used for the determination of physical and morphological properties, and the logs were used for the analysis of mechanical properties, lumber quality after sawing and drying, and workability properties.

Morphological properties

In each cross-section, a line was drawn in the north-south direction and another perpendicular to it in the east-west direction, both passing through the pith. In these two directions, total diameter (TD), diameter without bark (DWB), and heartwood diameter (DHW) were measured (Fig. 1e). According to these measurements, the bark thickness (BT), heartwood (HWP), and bark (BP) percentages were calculated in relation to the total area of each tree sampled. BT was calculated as the difference between TD and DWB divided in two. Sapwood was not calculated because it is directly related to heartwood and bark. If the difference between 100 and the sum of the areas of heartwood and bark percentage could be calculated, then this value was not presented for the correlation between heartwood and sapwood.

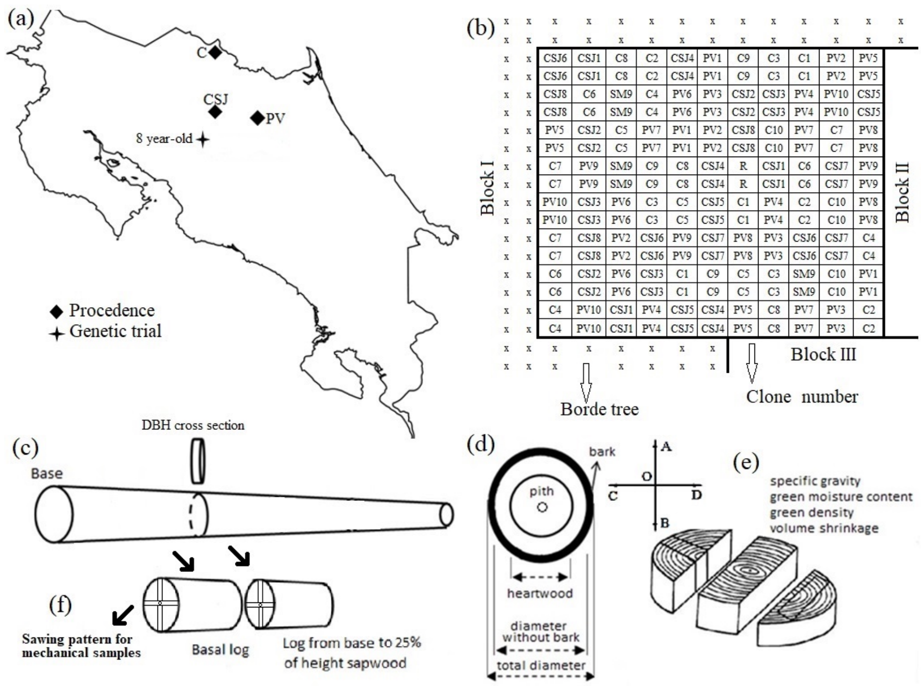

Figure 1: (a) Geographic localization of clonal test de *S. macrophylla* in Costa Rica, (b) tree plantation selected for wood properties studies, (c) sampled cross-section and log extraction from stem, (d) parameters measured in cross-section and (e) cross-section cut pattern for physical properties determination; (f) sawing pattern for mechanical properties

Physical and mechanical properties

Cross-sections were cut in the north-south direction (including the pith) with a width of 2.5 cm. These sections were divided into piths, obtaining two subsamples (Fig. 1f). These samples were used to determine specific gravity (SG), green moisture content (MC-G), and wood density (WD) under green conditions. Based on ASTM D-143-14, green weight/green volume and SG and MC-G are used to calculate WD.[42] The mechanical strengths determined were: compression parallel to the grain (CP), modulus of rupture (MOR), modulus of elasticity (MOE) in static bending, and shear strength parallel to the grain (SS), following ASTM D143-14.[42] The logs obtained from the sampled trees were sawn, and the pieces were dried to obtain the 12% MC condition. For each of the mechanical tests, 16 to 18 samples per clone were prepared, then 226, 240, and 225 samples for bending, shear, and compression testing, respectively. Although the mechanical properties of *S. macrophylla* have little importance because its use is oriented towards appearance grade products, these properties were determined for the purpose of characterising the clones.

Heartwood colour determination

Heartwood colour was measured at 2.54 cm and 5 cm thick in air-dry conditions. A Miniscan EZ 4500L was used, which estimates colour in three coordinates: lightness (L*), redness (a*), and yellowness (b*). The colour change (ΔE*) between the heartwood colour of clone wood and the heartwood colour of *S. macrophylla* trees in a natural forest was calculated. Natural forest samples (TECw-80 and TECw-943) from the Xylariorum of the Instituto Tecnológico de Costa Rica (TECw) were used. Wood samples were 5 years old, therefore there was little change induced by ageing. Wood samples from natural trees presented average parameters of L*=35.12, a*=15.25, and b*=17.85. ΔE* was calculated by summing the quadratic difference of each colour coordinate according to the ASTM D 2244-11 standard.[43] ΔE* represents the difference in wood colour between desirable wood, in this case, wood from trees growing in a natural forest, and wood from different clone trees. Low values of ΔE* indicate a minor to low (6%) difference in wood colour between trees from clones and those from a natural forest.

Wood quality during sawing and drying

Logs were sawn into 2.5 cm-thick boards, using a typical cutting pattern for lumber production in Costa Rica.[41] Subsequently, the boards were subjected to a drying process using a conventional Nardi dryer (Nardi, Italy), with a capacity of 6 m^3. The drying schedule proposed for the species was followed, with a total drying duration of 16 days.[21] The evaluation of drying defects was measured after sawing, before drying, and after drying. The parameters evaluated were: warping (twist, crook, bow, and cup), splitting, cracking, and collapsing. The methodology of Hallock and Malcom,[44] and Milota[45] was used to evaluate all drying defects. Drying defects were presented in two forms: (a) incidence, which represents the ratio between the number of boards with defects and the total number of boards expressed as a percentage, and (ii) magnitude of the defect, which represents the average of all the boards with drying defects presented.

Workability properties

Dried boards (2.5 cm thick, previously kiln-dried) were used. Ten boards with tangential cuts were selected for each clone. The tests performed were: planning using two feed rates (6 and 30 m*min^{-1}); sanding and turning using four cutting angles (10°, 15°, 40°, and 60°); and were carried out following the specifications of ASTM D-1666-93.[46] For the turning, planning, and sanding tests, the quality type and grading have been detailed in ASTM-D-1666-93[46] and Moya *et al.*[2]

Ranking of clones

For establishing the ranking of clones, two variables of growth or morphology properties (DBH and HWD) and two variables of wood properties (SG and ΔE*) were considered. The first two growth variables are important because they determine the productivity of the clones in plantations[22] and the two properties of the wood. SG is correlated with many other properties, and the colour of the wood is an important factor in the marketing of *S. macrophylla* wood.[29-34] Next, the clones were sorted from highest to lowest value, considering the variables evaluated, and the four top clones in diameter at breast height were analysed in relation to other wood properties with the objective of determining the best clone.

Statistical analysis

An analysis of variance (ANOVA) was performed using the SAS statistical program to compare morphological, physical, and mechanical properties, heartwood colour, and workability between clones. Differences between variables were determined by performing a Tukey test (P<0.05).

RESULTS AND DISCUSSION

Tree diameter and height, heartwood and bark content

The variation of DBH and heartwood (DHW and HWP) was similar, with clones C2, C4, and C5 having the lowest values, and clones C1, C6, and C207 presenting the highest values, and between these two groups, there are several clones with intermediate values (Table 1). In the HT parameter, clones C1, C2, and C6 presented the highest values of HT, and clone C13 was the one with the lowest value of HT, while the other clones presented intermediate values. In relation to BP variation, 3 groups were identified: clones C1, C13, C115, and C207 – with the statistically highest values; clone 4 – with the statistically lowest BP; and clones C2, C5, C6, and C207 – with intermediate values in both previous groups (Table 1).

DBH, H_T, D_{HW}, and WP obtained from different clones sampled at 8 years of age in Costa Rica (Table 1) presented lower values than those reported by Gilbero *et al.*[48] for wood from trees of the same age and different seed provenances planted at two sites in the Philippines. However, the values of these parameters for the genotypes evaluated in the present study (Table 1) were higher than those reported by Sudrajat *et al.*[16] for different progeny planted in Bogor, but they sampled trees that were 10 years old and 3 different progenies (Nicaragua, Panama, and Mexico) planted in Puerto Rico.

Considering the results obtained by Gilbero *et al.*[47] and Sudrajat *et al.*[16] for DBH, HT, and DHW and the values obtained for these wood properties in the present study, it is possible to affirm that the clones studied presented good development (Table 1). Considering the clones with the highest values of those three parameters (clones 1, 6 and 207), thereby placing them as the best clones when the genetic ranking was established (Fig. 3).

Table 1
Diameter at breast height and total height of trees, characteristics of heartwood and bark at diameter at breast height for different *S. macrophylla* clones grown in Costa Rica

Clone	Diameter at breast height (cm)	Total height (m)	Heartwood diameter (cm)	Heartwood percentage	Bark percentage
C1	16.28^{A}	13.70^{A}	12.30^{A}	56.99^{A}	18.56^{A}
C2	13.68^{BC}	14.00^{A}	9.20^{BC}	45.48^{BC}	15.14^{B}
C4	12.33^{C}	11.25^{C}	8.83^{C}	51.28^{B}	11.10^{C}
C5	13.20^{BC}	12.93^{B}	8.48^{C}	41.14^{C}	15.00^{B}
C6	17.13^{A}	14.40^{A}	12.40^{A}	52.79^{B}	14.08^{B}
C13	14.10^{B}	10.65^{C}	10.33^{B}	53.70^{B}	18.23^{A}
C79	13.80^{B}	11.40^{BC}	9.70^{B}	49.15^{BC}	19.12^{A}
C115	14.90^{B}	12.10^{B}	10.33^{B}	48.07^{BC}	20.63^{A}
C207	15.20^{AB}	12.70^{B}	11.28^{AB}	55.56^{A}	15.50^{B}

Note: Different letters mean statistical differences at 99% among clones

Thus, these results indicate the possibility of increasing plantation productivity through the appropriate use of clones, but they presented low values of SG and high values of colour change (Table 5).

In this regard, different studies have shown clone variability.[16,39,47] Abarquez *et al*.[39] and Sudrajat *et al*.[16] reported high variability for the DBH and other woods (Table 1). According to Sudrajat *et al*.[16] and Gillies *et al*.,[48] the high variability was attributed to the high genetic diversity of the species in America.[49]

Wood colour

Table 2 shows the colour parameters and colour change (ΔE*) in relation to the wood colour of natural forest trees. For the L* parameter, clones 1 and 5 presented the highest values; on the contrary, clones C2, C79, and C115 presented the lowest values. In parameter a*, clones C4 and C79 presented statistically lower values than the rest of the clones. In parameter b*, clones 2, 4, and 79 presented the highest values, and clones C1 and C13 were the clones with the lowest values (Table 2). In relation to ΔE*, three groups can be established: clones C79 and C115 – with the lowest values of ΔE*, followed by clones C2, C4, C6, C13, and C207 – with values of ΔE* between 20.42 and 23.79, and the last group, with the highest ΔE* values, included clones C1 and C5 (Table 2).

The average of the three parameters (L*, a*, and b*) was lower in the wood of the clones in relation to the values of the wood from the natural forest (Table 2). In order to visually show the difference in colour between wood from plantations and wood obtained from natural forest trees, Figure 2 is presented. For heartwood from plantations (Fig. 2a), the colour is lighter than that of wood from natural forests (Fig. 2c). Meanwhile, the colour of the sapwood from the clones (Fig. 2d) is lighter than the heartwood from both plantation trees (Fig. 2a) and natural forests (Fig. 2c).

An important wood characteristic in the commercialisation of *S. macrophylla* wood is its colour.[1] However, in the case of the wood of the clones evaluated at 8 years old, which presented a lighter tone than the wood of the natural forest (Fig. 2), as a consequence, the wood from the clones evaluated presented greater lightness (L*), lower redness (a*), and higher yellowness (b*) in relation to the wood from the natural forest (Table 2). The wood with this characteristic can affect the commercialisation of lumber from clones at an early age since the market for this species is generally associated with a brown colour,[1] and the wood of the clones at an early age does not have this feature.

However, despite this inconvenience, clones 79 and 115 presented lower ΔE* values, which means a lighter colour compared to natural forest wood. However, the colour parameters vary with age; the L* decreases, the a* increases, and the b* decreases, giving the wood a darker tone,[53] in addition to the fact that the dark colour may increase with age[54] and the colour of the wood tends to be darker with a tendency towards brown, and in this way improving the possibility that the wood of the clones can be commercialised more easily on the market.

Table 2
Wood color parameter for different *Swietenia macrophylla* clones grown in Costa Rican plantations, compared to wood from natural forest trees

Clone	Wood color parameter			ΔE*
	Lightness (L*)	Redness (a*)	Yellowness (b*)	
C1	57.79^{A}	18.33^{A}	28.00^{A}	25.84^{C}
C2	51.03^{BC}	18.53^{A}	26.71^{B}	20.42^{B}
C4	53.79^{B}	17.56^{B}	25.27^{BC}	22.71^{B}
C5	56.22^{A}	19.43^{A}	30.52^{A}	26.01^{C}
C6	54.59^{B}	18.03^{A}	29.00^{A}	23.79$_{B}$
C13	53.51^{B}	18.82^{A}	27.27^{AB}	21.37^{B}
C79	47.36^{C}	18.13^{AB}	24.77^{C}	15.91^{A}
C115	48.80^{C}	19.20^{A}	26.14^{B}	17.44^{A}
C207	54.53^{B}	17.95^{A}	26.89^{B}	22.54^{B}
Average	53.21	18.42	27.31	21.95
Forest wood	35.12	15.25	17.85	-

Note: Different letters mean statistical differences at 99% among clones

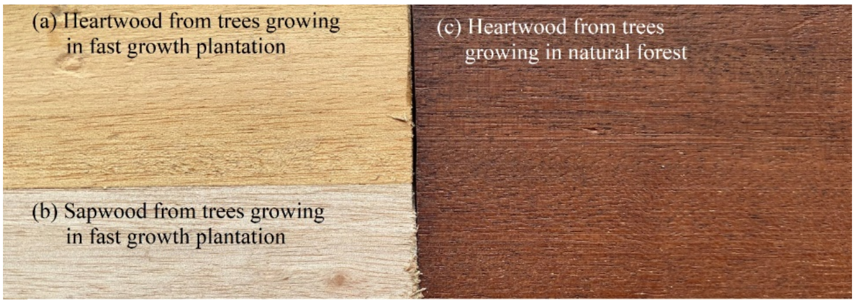

Figure 2: Comparison wood color between trees from fast-growth plantation and natural forest: (a) heartwood and (b) sapwood from plantation and (c) heartwood from natural forest

Table 3
Physical and mechanical properties at DBH for different *S. macrophylla* clones grown in Costa Rica

Clone	Specify gravity	Green density (g/cm^3)	Green moisture content (%)	Bending test MOR (Mpa)	Bending test MOE (Gpa)	Compression stress (MPa)	Stress shear (MPa)
C1	0.48^{BC}	0.80^{BC}	67.45^{A}	55.40^{D}	6.33^{D}	35.76^{C}	13.97^{B}
C2	0.48^{BC}	0.78^{C}	62.16^{B}	73.38^{A}	8.40^{A}	41.47^{A}	15.01^{A}
C4	0.48^{BC}	0.77^{CD}	61.26^{BC}	65.31^{C}	7.92^{AB}	35.90^{C}	12.46^{C}
C5	0.47^{BC}	0.78^{C}	65.40^{A}	65.13^{C}	7.62^{B}	35.96^{C}	13.04^{BC}
C6	0.45^{C}	0.75^{C}	67.60^{A}	64.07^{C}	7.65^{B}	35.76^{C}	13.13^{BC}
C13	0.49^{AB}	0.84^{B}	69.88^{A}	56.63^{C}	5.70^{D}	34.42^{C}	12.97^{BC}
C79	0.50^{AB}	0.79^{C}	59.07^{C}	65.18^{C}	7.11^{C}	42.40^{A}	14.33^{B}
C115	0.53^{A}	0.87^{A}	62.78^{B}	74.31^{A}	7.13^{C}	42.95^{A}	15.20^{A}
C207	0.50^{AB}	0.82^{B}	62.59^{B}	68.70^{B}	7.29^{BC}	38.58^{B}	14.03^{B}

Note: Different letters mean statistical differences at 99% among clones

Then, according to these results and the clone evaluated, clones C79 and C115 may be represented as having the desirable colour due to the fact that their wood colour is related to age (older trees produce wood with a darker colour).[55] Another important observation is that wood from a natural forest was stored for 5 years, and since colours change with age, ΔE* may have induced effects on these values.

Physical and mechanical properties

Table 3 shows the physical and mechanical properties at DBH of the different genotypes of *S. macrophylla*. Statistically, for SG, clones C2, C13, C79, C115, and C207 presented the highest values, and clone C6 the lowest. In the WD values, the highest value was found in clone C115 and the lowest value in clones C2, C4, and C5, C1, C6, and C13, with the lowest value in clones C4 and C79 (Table 3).

The evaluation of MOR among the different genotypes showed that clones C2 and C115 were the ones with the highest values, followed by clone 207, then a group composed of clones C4, C5, C6, C13, and C79, and the one with the lowest MOR value was clone 1. In terms of MOE, four groups were identified: a group composed of clones C2 and C4 had the highest value, followed by a group composed of clones C5 and C6, followed by a group composed of clones C79 and C115, and a group composed of clones C1 and C13 with the lowest value (Table 3). In the resistance to CP, 3 groups of clones were established: the first, with the highest CP values, was formed by clones C2, C79 and C115; the second group was only of clone C207; and the third group, with lowest CP value, was formed by clones C1, C4, C5, and C6. In the SS property, clones C2 and C115, followed by clones C1, C5, C6, C13, C79, and C207, and finally clone C4, presented the lowest resistance in SS (Table 3).

The clones of *S. macrophylla* with the lowest SG values were C1, C2, C4, C5, C6, and C13, with values lower than 0.49 (Table 2). When they were compared with the SG of trees with a higher age in plantations or from natural forests, their values were lower. For example, the following studies reported SG higher than 0.50: Anoop *et al.*[29] in 90-year-old trees; Langbour *et al.*[32] in trees for ages 16 to 60 years; De Carvalho *et al.*[25] in trees from 18-year-old plantations; Sharmin *et al.*[34] for trees aged 14 to 17 years; Pereira *et al.*[31] in plantations of 70 years; Sudrajat *et al.*[16] on a 20-year shade tree; Briscoe *et al.*[30] for trees of different ages; and Ashaduzzaman *et al.*[36] for trees of 20 and 15 years. However, clones C79, C115, and C207 presented SG values between 0.50 and 0.53, a range close to those reported by the authors previously mentioned.

Likewise, both clones with SG values less than 0.50 and those with SG values greater than this value, when compared with studies on younger trees, such as those carried out by Langbour *et al.*[33] in plantations less than 40 years old, Gilbero *et al.*[47] in 8-year-old plantations, Abarquez *et al.*[39] for plantations of 50 months, and Mendoza *et al.*[37] with trees of 10 and 28 years reported SG values less than 0.49, values within the SG range of the different clones studied (Table 2).

The SG parameter is one of the most important properties of wood because it is correlated with many other physical-mechanical properties, such as shrinkage, workability, and behaviour in end applications, among others.[55] For example, higher SG values are associated with higher mechanical resistance,[55] as was observed in the present study (Table 3). Thus, clones C79, C115, and C207 were in the highest categories in the ranking of clones using SG (Table 4), and when mechanical properties were used for classification (MOR and MOE, CP and SS), these clones were also located in the highest positions (Table 4). On the contrary, the clones with the lowest values of SG (clones C6, C1, C2, and C4) were also located in the lowest positions of the mechanical properties (Table 4). Although the mechanical properties were evaluated in this study, it is important to mention that wood from this species for structural uses will probably be limited since wood from *S. macrophylla* is oriented towards uses where appearance is more important.[2]

Although it is observed that the general, physical, and mechanical properties of the clones in the present study were lower than those in the data reported by other studies, which are important wood properties, the values of SG reached appropriate values at 8 years old, and then good mechanical properties were also found. So, despite its juvenile state, it can be used in structural applications due to its adequate mechanical properties, compared to other plantation wood grown under fast-growing conditions in Costa Rica.[21]

Correlation between different wood characteristics

DBH was the most important wood parameter correlated with other wood properties; it was significantly correlated with tree height (HWD) and negatively correlated with ΔE* and SG. Tree height was positively related to HWD and BP. L*, the colour parameter, was correlated with ΔE*. SG was positively correlated with WD, shear, and compression stresses. Finally, MOE was positively correlated with shear stress and negatively correlated with compression stress (Table 4).

Table 5
Ranking of main wood properties studied for 9 *S. macrophylla* clones

Ranking position	Diameter at breast height (DBH)	Heartwood diameter (HWD)	Specify gravity (SG)	Color change (ΔE*)
1	C2	C6	C115	C4
2	C1	C1	C207	C2
3	C207	C207	C79	C207
4	C115	C115	C1	C1
5	C13	C13	C2	C5
6	C6	C79	C13	C115
7	C79	C5	C4	C6
8	C5	C2	C5	C13
9	C 4	C4	C6	C79

Table 4
Pearson correlation coefficient between different wood properties for 9 clones of *S. macrophylla*

Parameter	Morphological properties					Wood color				Physical properties			Mechanical properties			
	DBH	Tree height	HWD	HWP	BP	L*	a*	b*	ΔE*	SG	WD	MC-G	MOE	MOR	Shear stress	Compression stress
DBH	1.00															
Tree height	0.85**	1.00														
HWD	0.86**	0.68**	1.00													
HWP	-	-	-	1.00												
BP	-	-0.75**	-	-	1.00											
L*	-	-	-	-	-	1.00										
a*	-	-	-	-	-	-	1.00									
b*	-	-	-	-	-	-	0.65*	1.00								
ΔE*	-0.62*	-	-	-	-	0.65*	-	-	1.00							
SG	-0.61*	-	-	-	-	-	-	-	-	1.00						
WD	-	-	-	-	-	-	-	-	-	0.77**	1.00					
MC-G	-	-	-	-	-	-	-	-	-	-	-	1.00				
MOE	-	-	-	-	-	-	-	-	-	-	-	-	1.00			
MOR	-	-	-	-	-	-	-	-	-	0.65*	-	-	-	1.00		
Shear stress	-	-	-	-	-	-	-	-	-	0.60*	-	-	0.59*	0.75**	1.00	
Compression stress	-	-	-	-	-	-	-	-	-	-	-	-	-0.59*	-	-	1.00

Ranking of clones

The four clones at the top of the DBH variable show that clone C2 had low values of HWD, a medium SG value, and a high ΔE* value (Table 5). While clone C1 presented good development of HWD, it presented an average value of SG and ΔE*. Clone C107, located third in terms of DBH and HWD parameters, despite having high SG, had high ΔE* values. Finally, clone C115 presented high potential since it had high SG values and low ΔE* values (Table 5).

Clones C1 and C2 are important for wood production (volume) because they are in the top position in the ranking for the diameter parameter. In relation to the other variables (SG and colour change), it was observed that clones C1 and C2 had good development for DBH and HWD and were located in the middle for SG ranking and in the top position for wood colour change (Table 5), a behaviour that is to be expected due to the negative correlation between these variables (Table 4). So, although the clone presented the highest growth in diameter (total and heartwood), it has the disadvantage that the SG is low and it presents a colour change of greater magnitude in relation to natural forest wood. Although *S. macrophylla* does not have uses oriented towards structural components, a low SG brings with it low mechanical properties due to the correlation with some mechanical properties (Table 4). However, the change in colour would be a major inconvenience since the wood of this species and its commercialisation are focused on these important wood characteristics. Then, the next clones with good development were C207 and C115, which presented adequate SG, but when ΔE* was changed, clone C207 presented high colour change values, but C115 showed low values of ΔE*. So, if considering an equilibrium between growing parameters and wood properties, clone 115 presented important potential for planting in a fast-growth plantation.

Lumber quality during sawing and drying

The evaluation of lumber quality (warps, checks and splits during sawing and drying) is presented in Table 6. Regarding warp defects after the sawing process, it was observed that cupping and twisting were not recorded after sawing. In the other two defects (bow and crooking), the magnitude was low in all clones: from 1 mm to 3 mm for bow and from 1 mm to 4 mm for crooking; however, the incidence varied among different clones. In clones C2, C13, and C57, the incidence was higher than 57%; in clones C1, C4, C6, and C115, the incidence varied between 30% and 39%; and in clones 5 and 79, the incidence was less than 20%. As regards the crooking defect, for clones C2, C13, and C57, the incidence was higher than 57%, but clones 4 and 6 were added to this group, while the rest of the clones (C1, C5, C79, and C115) had an incidence ranging from 40% to 47%.

Speaking about the split defect, it was not present in clones 4 and 13. On the other hand, for clones 5 and 6, the magnitude and incidence were low, while the rest of the clones (C1, C2, C79, C115, and C207) presented a magnitude over 10 mm, and the incidence varied between 14% and 25%. As for the checking defect, clone C13 did not present it, clones 1 and 5 had a low magnitude and incidence, and the rest of the clones had a magnitude ranging from 20 mm to 56 mm and an incidence ranging from 15% to 29% (Table 6).

In the evaluation of the quality of the lumber-dried samples, it was observed that the presence of cup defects was the one with the highest incidence (Table 6). A defect of this type did not affect clones C2 and C79; following that, clones C4 and C13 were less than 14% affected, and for other clones the incidence ranged from 19% to 27%. In the case of the bow defect, it was also of low magnitude, but the incidence was less than 30% in clones C5, C6, and C79, while other clones ranged from 38% to 55%. Despite its low magnitude, the crook defect had the highest percentage of incidence of all the defects in dried lumber (Table 6). For clones C2, C5, and C13, the percentage was less than 27%; for clones C79 and C115, it varied between 40% and 43%; and for the other clones, the incidence percentage was greater than 50%.

With regard to the twist defect, it is one of significant incidence, but lower than the crook and also of low magnitude. Clone 13 did not present this defect, clones C2, C4, and C79 presented values between 5% and 15%, clones 1, 6, and 207 had an incidence of 20% and 24%, and other clones had a percentage of 33 to 36%. Regarding split defects, they were also of high magnitude, ranging from 5 mm to 90 mm. The incidence was low in clone 4, the clones C1, C2, C6, C13, C115, and C207 varied from 13 to 15%, and clones C5 and C79 had the highest percentages, between 21% and 27%. The check defect was accentuated in several clones, over 55 mm up to 199 mm, with the exception of clone 2, which presented low magnitude but high incidence. The incidence was low in clone C4, but in the other clones, in addition to presenting a high magnitude, the incidence was between 33 and 40% (Table 6).

Workability properties

The behaviour of the wood in each of the clones for the different workability parameters is presented in Table 7. In planning, there were no significant differences between the different clones, considering the two feed rates and the quality of planning; that is, all the clones produced wood with an excellent classification, which represented an area free of defects between 80% and 100%. In the sanding operation, again, there were no statistical differences between the different clones in terms of temperature or dust removal. Since all clones were sanded at a low temperature, it was classified as easy sanding. In the turning test, the surface quality generally ranged from excellent to good; however, for clones C2, C13, C39, and C115, when turning at an angle of 40°, the surface quality was fair in the parallel plane. In the parallel plane, it is possible to observe that, as the inclination increased in degrees, the quality decreased, and defects were observed on the wood surfaces. Otherwise, in the perpendicular plane, very good surfaces with minimal defects were recorded. The best qualities in most of the clones were found in the parallel plane at angles of 0° and 15°, with the exception of clones 5, 6, and 79, where it was possible to observe some type of defect, lowering the quality of the surface later in the turning process.

The behaviour of wood in sawing, drying, and workability processes varied within the same species, and between clones was no exception. In the sawing or drying processes, lumber quality was generally associated with the presence of growth stress,[56] which is accentuated in young trees and mainly grows in fast-growth conditions.[57] Thus, it was not possible to observe a clear tendency in lumber quality from each of the clones evaluated due to the large variation between clones. For example, some clones presented low incidence of bow and crook after sawing, but in other defects, such as split or crack, they had high incidence (Table 4).

Likewise, the same behaviour was observed in lumber quality after kiln drying or in workability characteristics (Table 5). Some clones have low incidence of defects in some parameters, but in others, the values of other properties were high (Tables 5-6). Probably, it was not possible to establish the influence of the clones on lumber quality after sawmilling and drying or on workability because the age of the trees was still insufficient and there was a large influence of growth stress, which is high in trees of short-rotation tropical species[58] and does not express the genetic effect of each clone.

In general, it was observed that different clones presented normal values of incidence of defects after sawing or drying (Table 4), in addition to good properties of planning and sanding, but some problems during turning, a situation that is normal in wood from trees originating from plantations with juvenile ages[2,28] due to the fact that those trees present a high percentage of juvenile wood,[8] in which the fibre had few lignified tissues or a greater fibril angle.[9]

On the other hand, despite the fact that it was not yet possible to establish which clone has good lumber quality after sawing, kiln drying, or workability conditions under which the clones were evaluated, the results obtained were compared with those for other species of medium wood density and also used in commercial reforestation.[21] So, we can establish that the clones at the age of 8 years produced wood with low warping after drying and sawing and good workability properties. A better chance of finding a good clone requires screening them, in addition to establishing clones with better wood properties.

Table 6
Lumber quality: incidence and magnitude of cup, twist, bow, crook, check and split during sawing and drying for different *Swietenia macrophylla* clones grown in Costa Rica

Clone	Parameter	Lumber defects after swing				Lumber defects after drying					
		Bow	Crook	Split	Check	Cup	Bow	Crook	Twist	Split	Check
C1	Incidence (%)	35	40	25	10	25	45	65	20	15	40
	Magnitude (mm)	1	2	13	9	2	2	3	2	41	199
C2	Incidence (%)	65	65	25	15	0	55	25	15	15	40
	Magnitude (mm)	1	1	10	56	0	2	2	0	13	7
C4	Incidence (%)	36	57	0	29	14	7	64	7	6	7
	Magnitude (mm)	1	4	0	23	2	1	6	0	20	128
C5	Incidence (%)	20	47	7	7	27	27	27	33	27	33
	Magnitude (mm)	1	4	3	5	2	1	3	3	90	198
C6	Incidence (%)	39	64	4	29	25	29	64	25	14	39
	Magnitude (mm)	1	4	1	45	1	1	5	2	27	135
C13	Incidence (%)	69	62	0	0	8	38	23	0	15	23
	Magnitude (mm)	3	4	0	0	2	2	2	0	5	55
C79	Incidence (%)	21	43	21	21	0	29	43	36	21	36
	Magnitude (mm)	1	3	9	23	0	1	3	2	29	86
C115	Incidence (%)	30	50	20	25	20	50	40	10	15	40
	Magnitude (mm)	1	2	17	20	2	1	2	1	33	127
C207	Incidence (%)	57	57	14	24	19	52	57	24	14	38
	Magnitude (mm)	1	3	7	33	2	1	4	2	46	159

Table 7
Workability for properties for different clone sampled of *Swietenia macrophylla* growing in Costa Rica

Clone	Planning		Sanding		Turning					
	6 m/min	20 m/min	Temperature (°C)	Removal of dust	Angle 0°	Angle 15°	Angle 40º		Angle 60º	
					Paralel	Paralel	Paralel	Perpendicular	Paralel	Perpendicular
C1	95^{A} EX	92^{A} EX	28.32^{A} B	2.09^{A} VE	EX (AD)	EX (AD)	GO (RG)	EX (AD)	GO (RS)	GO (RG)
C2	99^{A} EX	98^{A} EX	27.83^{A} B	1.72^{A} VE	EX (AD)	EX (AD)	GO (RS)	GO (RG)	FA (RG)	EX (AD)
C4	95^{A} EX	91^{A} EX	28.29^{A} B	1.85^{A} VE	EX (AD)	EX (AD)	GO (RS)	EX (AD)	GO (RS)	EX (AD)
C5	96^{A} EX	97^{A} EX	27.22^{A} B	1.99^{A} VE	EX (AD)	GO (RS)	GO (RG)	EX (AD)	GO (RS)	EX (AD)
C6	98^{A} EX	98^{A} EX	28.15^{A} B	2.56^{A} VE	GO (RS)	GO (RS)	GO (RG)	EX (AD)	GO (RG)	EX (AD)
C13	95^{A} EX	98^{A} EX	27.58^{A} B	2.06^{A} VE	EX (AD)	EX (AD)	GO (RS)	EX (AD)	FA (RG)	EX (AD)
C79	98^{A} EX	94^{A} EX	26.46^{A} B	2.37^{A} VE	EX (AD)	GO (RS)	GO (RS)	GO (RG)	FA (RG)	EX (AD)
C115	97^{A} EX	95^{A} EX	27.55^{A}B	1.71^{A} VE	EX (AD)	EX (AD)	GO (RS)	EX (AD)	FA (RG)	EX (AD)
C207	96^{A} EX	94^{A} EX	27.34^{A} B	1.80^{A} VE	EX (AD)	EX (AD)	GO (RS)	GO (RG)	GO (RG)	EX (AD)

Note: Different letters between species and same test workability mean 99% statistical difference, and letters in parenthesis represent quality and classification. For planning: EX: excellent, GO: good, FA: fair, PO: poor, VP: very poor. For temperature and dust removal in sanding test: L: low, M: medium, H: high, L-M: low to medium, M-H: medium to high, VE: very easy, VD: very difficult. In turning test: FG: fluffy grain, RG: ripped grain, AD: Any defects, RS: rough surface

CONCLUSION

The results presented in this study for *S. macrophylla* should be considered as an effort towards improving the wood properties of this species. Future research is needed to validate and contrast these findings with those of old wood. Differences in morphological characteristics were few, except for tree diameter and heartwood parameters (D_{HW} and HWP). However, other wood properties presented a large variation in wood properties. Thus, they give *S. macrophylla* the potential to breed favourable wood properties.

The workability properties of the wood from each of the clones were classified as good, considering that all clones had a high presence of young wood. The defects with the highest incidence after drying were cracks, warping, and cupping, and this last defect presented a low incidence percentage. However, because the clones were evaluated at a young age, there was little variability in the clones' workability properties.

The results showed that diameter, height, and heartwood showed good development and that clones C1, C2, and C207 were the best clones. However, if focusing on an equilibrium between growing parameters and wood properties, clone 115 presented important potential for planting in a fast-growth plantation, considering its stable workability properties.

REFERENCES

[1] H. Krisnawati, M. Kallio and M. Kanninen, *Swietenia macrophylla* King. Ecology, Silviculture and Productivity, CIFOR, 2011, 14 p. Bogor, Indonesia, https://www.cifor.org/publications/pdf_files/Books/BKrisnawati1104.pdf

[2] R. Moya, C. Salas, A. Berrocal and J. C. Valverde, *Maderas y Bosques*, **21**, 31 (2015), https://doi.org/10.21829/myb.2015.210424

[3] J. Forero-Montaña, J. K. Zimmerman, E. González, F. Wadsworth, S. Ward *et al.*, *Trees For. People*, **5**, 100 (2021), https://doi.org/10.1016/j.tfp.2021.100113

[4] L. K. Snook, in "Timber, Tourists and Temples: Conservation and Development in the Maya Forest of Belize, Guatemala and Mexico", edited by R. Primack, D. B. Bray, H. Galleti and I. Ponciano, Island Press, Washington DC, USA, 1998, pp. 61-80, https://ethz.ch/content/dam/ethz/special-interest/usys/ites/ecosystem-management-dam/documents/EducationDOC/EM_DOC/1997%20Brokaw%20et%20al%20Toward%20sustainable%20forestry%20in%20Belize.pdf#page=83

[5] F. B. Lamb, "Mahogany of Tropical America: Its Ecology and Management", University of Michigan Press, Ann Arbor, 1966, 220 pp.

[6] J. Grogan and P. Barreto, *Conserv. Biol.*, **19**, 973 (2005), https://www.jstor.org/stable/3591090

[7] J. Pérez, "Manual para el cultivo de la caoba", Informe Tecnico 1. Instituto Laudato Si. Centro de Investigación, Enseñanza y Producción Agroforestal (CEPIAGRY), Perú, https://www.laudatosiinstitute.org/wp-content/uploads/manual-de-caoba-ISBN.pdf.2017

[8] B. Zobel, *Tappi J.*, **64**, 61 (1981)

[9] B. Zobel, *Wood Sci. Technol.*, **18**, 1 (1984), https://doi.org/10.1007/BF00632127

[10] A. Murat, *Eurasian J. For. Sci.*, **8**, 60 (2020), https://doi.org/10.31195/ejejfs.661352

[11] F. Turchetto, M. M. Araujo, A. M. Griebeler, D. G. Rorato, A. L. Berghetti *et al.*, *J. Env. Manag.*, **269**, 110830 (2020), https://doi.org/10.1016/j.jenvman.2020.110830

[12] B. H. Trisasongko and D. Paull, *Geocarto Internat*, **35**, 317 (2020), https://doi.org/10.1080/10106049.2018.1516245

[13] H. X. Wu, *Scandinavian J. For. Res.*, **34**, 352 (2019), https://doi.org/10.1080/02827581.2018.1487579

[14] C. P. Liu, *Quart. J. Chinese For.*, **3**, 41 (1970)

[15] B. N. Gutiérrez, E. H. Cornejo, B. Rodríguez, J. López, M. H. Gutiérrez *et al.*, *Rev. Mexicana Cienc. Forest.*, **7**, 51 (2016), https://www.scielo.org.mx/pdf/remcf/v7n37/2007-1132-remcf-7-37-00051-en.pdf

[16] D. J. Sudrajat, Y. Ayyasy, I. Z. Siregar and L. Karlinasari, *IOP Conf. Series*: *Earth Env. Sci.*, **918**, 012042 (2021), https://doi.org/10.1088/1755-1315/918/1/012042

[17] K. Gerhardt and D. Fredriksson, *Biotropica*, **27**, 174 (1995), https://doi.org/10.2307/2388993

[18] O. Chinchilla, E. Corea and V. Meza, *Rev. Cienc. Amb.*, **54**, 180 (2020), http://dx.doi.org/10.15359/rca.54-2.10

[19] O. Chinchilla, E. Corea, V. Meza and C. Ávila, *Rev. For. Mesoamericana Kurú*, **18**, 62 (2021), http://dx.doi.org/10.18845/rfmk.v16i42.5540

[20] E. Corea-Arias, O. Chinchilla-Mora, V. Meza-Picado and C. Ávila-Arias, *Rev. For. Mesoamericana Kurú*, **17**, 94 (2020), https://doi.org/10.18845/rfmk.v17i41.5292

[21] R. Moya, C. Tenorio, J. Salas, A. Berrocal and F. Muñoz, in "Tecnología de la madera de plantaciones forestales", Editorial Universidad de Costa Rica, Cartago, Costa Rica, 2019

[22] A. C. P. Nunes, G. A. Santos, M. D. V. Resende, A. D. Silva, A. Higa *et al.*, *Sci. For.*, **44**, 563 (2016), https://doi.org/10.18671/scifor.v44n111.03

[23] G. Makouanzi, G. Chaix, S. Nourissaier and P. Vigneron, *South. For. J. For. Sci.*, **80**, 151 (2018), https://doi.org/10.2989/20702620.2017.1298015

[24] J. Gion, A. Carouché, S. Deweer, F. Bedon, F. Pichavant *et al.*, *BMC Genom.*, **12**, 301 (2011), https://doi.org/10.1186/1471-2164-12-301

[25] S. R. De Carvalho, J. S. De Holanda and P. N. Da Silveira, *Brazilian J. An. Env. Res.*, **4**, 2749 (2021), https://doi.org/10.34188/bjaerv4n2-096
[26] D. M. Gilbero, W. P. Abasolo, M. Matsuo and H. Yamamoto, *J. Trop. For. Sci.*, **34**, 1 (2022), https://doi.org/10.26525/jtfs2022.34.1.1
[27] W. J. León, *Rev. For. Venezolana*, **54**, 169 (2010)
[28] R. Moya and F. Muñoz, *J. Trop. For. Sci.*, **22**, 317 (2010), https://jtfs.frim.gov.my/jtfs/article/view/935
[29] E. V. Anoop, C. M. Jijeesh, C. R. Sindhumathi and C. E. Jayasree, *Res. J. Agri. For. Sci.*, **2**, 7 (2014), http://www.isca.me/AGRI_FORESTRY/Archive/v2/i8/2.ISCA-RJAFS-2014-037.pdf
[30] C. B. Briscoe, J. B. Harris and D. Wyckoff, *Carribean For.*, **24**, 67 (1963), https://www.srs.fs.usda.gov/pubs/ja/1963/ja_1963_briscoe_004.pdf
[31] P. Perera, H. Amarasekera and N. D. R. Weerawardena, *J. Trop. For. Environ.*, **2**, 26 (2012), https://doi.org/10.31357/jtfe.v2i1.567
[32] P. Langbour, J. Gérard, D. Guibal and R. T. Du Cros, *Bois For. Des. Trop.,* **298**, 3 (2008), https://doi.org/10.19182/bft2008.298.a20363
[33] P. Langbour, J. Gérard, J. M. Roda, P. A. Fauzi and D. Guibal, *J. Trop. For. Sci.*, **1**, 252 (2011), https://www.jstor.org/stable/23616969
[34] A. Sharmin, M. Ashaduzzaman and M. Shamsuzzaman, *Int. Res. J. Eng. Techn.*, **2**, 692 (2015), https://www.irjet.net/archives/V2/i5/IRJET-V2I5117.pdf
[35] J. G. Da Silva, V. B. Vidaurre, D. Minini, R. F. Oliveira, S. M. Rocha *et al.*, *Sci. For.*, **47**, 1 (2019), https://doi.org/10.18671/scifor.v47n121.01
[36] M. Ashaduzzaman, N. R. Mithun and A. Sharmin, *Indian J. For.*, **34**, 61 (2011), https://doi.org/10.54207/bsmps1000-2011-1C359S
[37] T. Mendoza, E. Alvarado and A. Elvir, *TATASCAN Rev. Téc. Cient.*, **20**, 53 (2008)
[38] A. A. Jara, E. D. Bello, S. V. A. Castillo, V. A. Fernandez and P. S. Madamba, *Philippine J. Sci.*, **137**, 159 (2008), https://philjournalsci.dost.gov.ph/images/pdf/pjs_pdf/vol137no2/pdfs/use_of_relative_density_based_schedules_in_kiln_drying.pdf
[39] A. Abarquez, D. Bush, J. Ata, J. R. Tolentino and D. Gilbero, *J. Trop. For. Sci.*, **1**, 314 (2015), https://jtfs.frim.gov.my/jtfs/article/view/942
[40] M. Chudnoff and T. F. Geary, *Turrialba*, **23**, 359 (1973)
[41] R. Serrano and R. Moya, *Rev. For. Mesoamericana Kuru*, **9**, 1 https://revistas.tec.ac.cr/index.php/kuru/article/view/370
[42] ASTM Standards, Vol. 4.10, ASTM D-143-22, 32 (2022), https://doi.org/10.1520/D0143-22
[43] ASTM Standards, Vol. 4.10, ASTM D-2244-21, 11 (2022), https://doi.org/10.1520/D2244-21
[44] H. Hallock and F. Malcolm, *Sawing to reduce warp in plantation red pine stud*. Research Paper FPL-RP-164 USDA Forest Service, Forest Products Laboratory, Madison, WI, 1972, https://www.fpl.fs.usda.gov/documnts/fplrp/fplrp164.pdf
[45] M. Milota, *For. Prod. J.*, **41**, 65 (1996)
[46] ASTM Standards, Vol. 4.10, ASTM D1666-17, 17 (2022), https://doi.org/10.1520/D1666-17
[47] D. M. Gilbero, W. P. Abasolo, M. Matsuo-Ueda and H. Yamamoto, *J. Wood Sci.*, **65**,1 (2019), https://doi.org/10.1186/s10086-019-1814-4
[48] A. C. M. Gillies, C. Navarro, A. J. Lowe, A. C. Newton, M. Hernandez *et al.*, *Heredity*, **83**, 722 (1999), https://doi.org/10.1046/j.1365-2540.1999.00626.x
[49] R. Moya, J. D. Marin, O. Murillo and L. Leandro, *Silvae Genetic.*, **62**, 142 (2013), https://doi.org/10.1515/sg-2013-0019
[50] C. Sotelo-Montes, R. E. Hernández, J. Beaulieu and J. C. Weber, *New For.*, **35**, 57 (2008), https://doi.org/10.1007/s11056-007-9060-9
[51] M. Susanto, T. A. Prayitno and Y. Fujisawa, *Indonesian J. For. Res.*, **5**, 135 (2008), https://doi.org/10.20886/ijfr.2008.5.2.135-146
[52] J. K. Vanclay, M. Henson and G. Palmer, *J. Wood Sci.*, **54**, 431 (2008), https://doi.org/10.1007/s10086-008-0977-1
[53] R. Moya and J. D. Marín, *New For.*, **42**, 329 (2011), https://doi.org/10.1007/s11056-011-9255-y
[54] T. Fujimoto, H. Akutsu, M. Nei, K. Kita, M. Kuromaru *et al.*, *J. For. Res.*, **11**, 343 (2006), https://doi.org/10.1007/s10310-006-0221-z
[55] S. Y. Zhang, *Wood Sci. Tech.*, **31**, 181 (1997), https://doi.org/10.1007/BF00705884
[56] J. Gril J. D. Jullien, S. Bardet and H. Yamamoto, *J. Wood Sci.*, **63**, 411 (2017), https://doi.org/10.1007/s10086-017-1639-y
[57] M. Kojima, H. Yamamoto, K. Okumura, M. Yoshida, T. Nakai *et al.*, *J. Wood Sci.*, **55**, 417 (2009), https://doi.org/10.1007/s10086-009-1057-x
[58] R. Moya, C. Tenorio and J. D. Torres, *For. Prod. J.*, **71**, 3 (2021), https://doi.org/10.13073/FPJ-D-20-00041