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Article

Physical and Mechanical Properties of Fast Growing Polyploid Acacia Hybrids (*A. auriculiformis* × *A. mangium*) from Vietnam

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Abstract: Acacia plants are globally important resources in the wood industry, but particularly in Southeast Asian countries. In the present study, we compared the physical and mechanical properties of polyploid *Acacia* (3x and 4x) clones with those of diploid (2x) clones grown in Vietnam. We randomly selected 29 trees aged 3.8 years from different taxa for investigation. BV10 and BV16 clones represented the diploid controls; X101 and X102 were the triploid clones; and AA-4x, AM-4x, and AH-4x represented neo-tetraploid families of *Acacia auriculiformis*, *Acacia mangium*, and their hybrid clones. The following metrics were measured in each plant: stem height levels, basic density, air-dry equilibrium moisture content, modulus of rupture (MOR), modulus of elasticity (MOE), compression strength, and Young's modulus. We found that the equilibrium moisture content significantly differed among clones, and basic density varied from pith-to-bark and in an axial direction. In addition, the basic density of AA-4x was significantly higher than that of the control clones. Furthermore, the MOR of AM-4x was considerably lower than the control clones, whereas the MOE of X101 was significantly higher than the control values. The compression strength of AM-4x was significantly lower than that of the control clones, but AH-4x had a significantly higher Young's modulus. Our results suggest that polyploid *Acacia* hybrids have the potential to be alternative species for providing wood with improved properties to the forestry sector of Vietnam. Furthermore, the significant differences among the clones indicate that opportunities exist for selection and the improvement of wood quality via selective breeding for specific properties.

Keywords: *Acacia* hybrid; polyploid *acacia*; triploid *acacia*; tetraploid *acacia*; moisture content; basic density; modulus of rupture; modulus of elasticity; ultimate stress in compression parallel to grain; Young's modulus

1. Introduction

Plants of the genus Acacia are an important resource in global furniture manufacturing and are vital to the wood industry of Southeast Asian countries [1–11]. Improvements in technology and tree breeding techniques have increased the interest in *Acacia* products [12]. An Acacia hybrid (an interspecific hybrid of *Acacia mangium* and *Acacia auriculiformis*) was first recognized in Malaysia in 1972 [10]; since then, this hybrid has rapidly become an important tree in the industrial output of many countries, including Vietnam.

Many studies on this *Acacia* hybrid, aimed at providing information for end-use applications, have shown that it is fast growing, has a medium strength, and can be utilized in many ways. For example, Kijkar (1996) demonstrated that the *Acacia* hybrid can grow to 8–10 m in height and 7.5–9.0 cm in diameter at breast height (DBH) in two years [13]. Another study indicated that, at 2.5–3.0 years of growth, the *Acacia* hybrid had produced a stem volume that was several times higher than that of *A. mangium* and *A. auriculiformis,* while at 4.5 years, it had produced twice the stem volume of *A. mangium* [14]. Although the *Acacia* hybrid has been shown to have a lower basic density than *A. auriculiformis* and a similar density to *A. mangium,* the shrinkage, modulus of rupture, and maximum strength in compression of these plants are not significantly different [7]. In contrast to these findings, Jusoh et al. [15] reported that the basic density and strength properties of the *Acacia* hybrid were significantly greater than those of second-generation *A. mangium*. Indeed, Rokeya et al. [16] compared the characteristics of the *Acacia* hybrid to those of teak, i.e., it is a moderately strong wood that is suitable for making furniture and household items. Three eight-year-old clones of the *Acacia* hybrid (namely HD3, K47, and H4) have also been compared with teak in their suitability for end-use applications [17]. In the study of these clones, the *Acacia* hybrid had a larger DBH than its original parent plant at the same age; however, the suitability indices of the three clones were slightly lower than those of the parent form [17]. The *Acacia* hybrid has also been shown to meet the requirements for use as pulp, use in the paper industry, and for certain various uses such as tool handles, furniture, and pallets [17]. Investigations into the wood properties of the *Acacia* hybrid clones [17–19] showed significant differences in their growth and in some wood properties. The effects of genetics and the environment on different *Acacia* hybrid clones have also been investigated. Studies show that the clone type and grown site significantly affect DBH and specific gravity (which can be estimated for the tree at a height of 3 m and anticipated at a young age [18]) [19–21]. However, significant differences in height and DBH are known to exist among clones at four and five years, but not at three years [21]. In Vietnam, the variation in *Acacia* wood properties is affected by climatic conditions; this variation is more visible in northern than in southern Vietnam [19]. Paiman et al. [22] examined the machining and physical properties of *Acacia* hybrid wood when it was stressed and non-stressed: non-stressed wood had better machining characteristics than stressed wood.

Several studies of the properties and anatomy of the *Acacia* hybrids have shown that it has great potential for fiber production. For example, Yahya et al. [23] found that the hybrid produced a higher pulp yield and had better paper strength than its pure form parents, *A. mangium* and *A. auriculiformis,* because it had thinner cell walls, a smaller proportion of ray cells, and a higher wood density than *A. mangium*. Jusoh et al. [15] also agreed that the *Acacia* hybrid could be used for pulp and paper production as its fiber length was greater than that of *A. mangium*. Similarly, Sharma et al. [24] found that three *Acacia* hybrid clones from India had longer fibers than those of *A. mangium* and *A. auriculiformis*. In contrast, Nirsatmanto et al. [12] reported no significant differences in the fiber lengths of the *Acacia* hybrid and its parent species [12]. Haque et al. [25] provided a broader perspective: the *Acacia* hybrid was the best among acacia species for pulpwood production in papermaking; however, the a-cellulose content and pulp properties of the *Acacia* hybrid were similar to those of *A. mangium* and *A. auriculiformis*. Other studies have also shown that the *Acacia* hybrid has properties, such as paper pulp yield and breaking strength, that are superior to its parent species [14,25].

Recently, *Acacia* hybrid plantation productivity and quality have been improved by using both cutting and tissue culture breeding technologies effectively in a large-scale clonal forestry. Research into, and the development of, breeding technologies has led to innovations in forestry and created cutting-edge methodologies [26], such as the breeding of polyploid *Acacia* hybrids that possess three or more sets of chromosomes [27]. This method is introducing diversity into breeding populations, reducing reproduction, fertility, and producing new wood fibers [3,28]. The advantages of polyploid *Acacia* hybrids have been described in several studies. For example, the Kraft pulp of eight-year-old tetraploid clones has been shown to have higher bulk, porosity, and tear strength than the pulp of diploid clones [29]. In addition, tetraploid clones are known to have longer and wider fibers than diploid clones [3,29]. Finally, the basic density of diploid and triploid *Acacia* hybrids has been compared in two locations in Vietnam [30].

Although some research on the properties of polyploid *Acacia* hybrids has been conducted in the studies cited above, there is currently a limited understanding of the various wood properties of the clones. Therefore, in the present study, we investigated the physical and mechanical properties of the wood from polyploid *Acacia* hybrid clones from Vietnam. The relationships among the wood properties and clones were also evaluated, with the aim of improving breeding programs.

2. Materials and Methods

2.1. Acacia Hybrid Polyploid Clones and Sampling

The materials used in this study were collected from nine *Acacia* hybrid clonal trials established by the Institute for Forest Tree Improvement and Biotechnology (Vietnamese Academy of Forest Sciences), between 2014 and 2018. The trial sites are located in Dong Nai (10°57′ N, 106°49′ E) in southern Vietnam. The soil type in the site is sandy alluvium, the mean annual rainfall is 1640 mm, and the mean annual temperature is 27 °C.

Acacia hybrid diploid (2x) clones available for commercial breeding, namely BV10 and BV16, were chosen as control clones. The best selection of commercial *Acacia* hybrids were transformed into tetraploid (4x) clones by in vitro colchicine treatment. Triploid (3x) clones could then be produced by pollination between 2x and 4x. Five ramets of each of the four 2x and 3x clones (i.e., BV10, BV16, X101, and X102), together with three 4x trees of tetraploid taxa (i.e., *A. auriculiformis*, *A. mangium*, and the *Acacia* hybrid) were felled at age 3.8 years to collect wood samples. Details of the clones are provided in Table 1.

Table 1. Polyploid materials at 3.8 years old used in the study.

Taxa	Clone/tree ID	Ploidy	Parental Information	No. of Ramets/Trees Sampled	DBH (cm)	Height (m)	Stem Volume (m^3)
Acacia hybrid	BV10	2x	Commercial diploid AH clones	5	13.0	16.0	0.21
	BV16	2x		5	12.6	15.0	0.19
Acacia hybrid	X101	3x	Controlled pollination (CP) between diploid AA and tetraploid AM	5	15.0	17.9	0.32
	X102	3x		5	14.4	16.6	0.27
A. *auriculiformis*	AA	4x	Colchicine-induced tetraploid trees of AA	3	11.8	10.1	0.11
A. *mangium*	AM	4x	Colchicine-induced tetraploid trees of AM	3	17.9	13.2	0.33
Acacia hybrid	AH	4x	Colchicine-induced tetraploid clones of AH	3	11.6	14.7	0.16

DBH, diameter at breast height.

Figure 1 illustrates the samples collected in this study. Logs that were 0.2–1.3 m and 1.5–3 m in length were taken from each tree stem after felling, to extract samples for measurement of mechanical properties. 5-cm disks were also taken to test physical properties at various height levels (0.2–13.5 m). Disk edges were coated with wax to prevent decay and other environmental alterations. DBH (1.3 m) was determined as the mean of two cross diameters. After felling, total height was also measured.

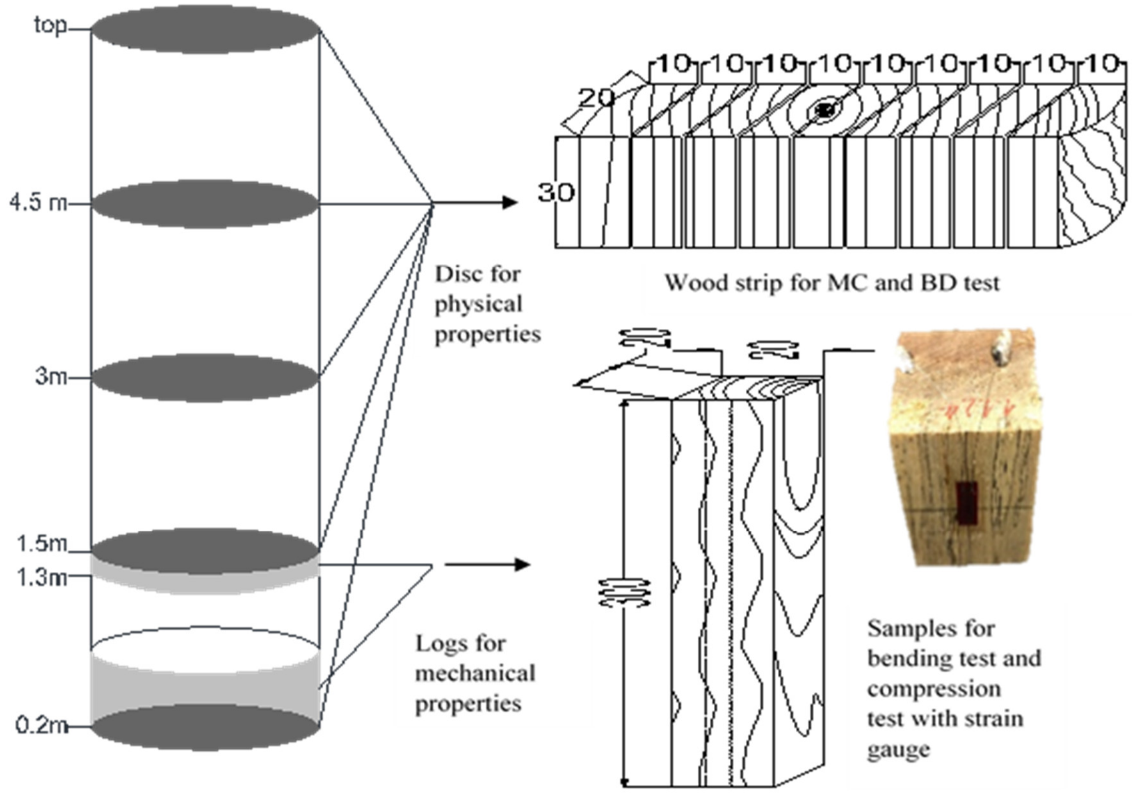

Figure 1. Sampling methods for discs and logs and test samples for physical and mechanical properties. (MC, moisture content; BD, basic density)

2.2. Air-Dry Moisture Content and Basic Density

Pith-to-bark strips (diameter × 30 × 20 mm) were cut from each disk after air drying. The strips were then divided into small pieces at a distance of 1 cm from pith-to-bark with a razor blade. Each piece was weighed at the air-dry stage and then dried at 103°C ± 3°C to determine dry weight. Equilibrium air-dry moisture content was determined at room temperature (around 25°C) and humidity (25–35% relative humidity (RH)). Basic density was measured with an electronic densimeter (EW-300SG, Alpha Mirage, Osaka, Japan). Samples for basic density measurements were soaked in distilled water for at least 24 h to ensure full hydration. They were then immersed and suspended using a metal shield inside the water bath of the densimeter to determine wood volume by water displacement. Samples were then oven-dried at 103 °C for around 48 h until they reached a constant mass; they were then re-weighted. Basic density was calculated as oven-dry mass divided by wood volume.

The change in basic density with the diameter growth of each disk is described as follows:

$$BD1 = BD_1$$

$$BD2 = \frac{1}{4}BD_1 + \frac{3}{4}BD_2$$

$$\cdots$$

$$BDn = \frac{1}{n^2}BD_1 + \frac{3}{n^2}BD_2 + \frac{5}{n^2}BD_3 + \cdots + \frac{2n-1}{n^2}BD_n$$

(where *BD1, BD2, … BDn* are basic densities for disk diameters of 1, 2, ... *n* cm, respectively; BD_1, BD_2, … BD_n are basic densities for samples at position 1, 2, … *n* cm).

2.3. Mechanical Testing

Specimens for static bending (20 × 20 × 320 mm, radial × tangential × axial) and compression (20 × 20 × 30 mm, radial × tangential × axial) were cut from a 20-mm-thick board. The specimens were conditioned to a constant mass at 20 °C ± 2 °C and a RH of 65% ± 5%. They were then maintained in this condition until required for testing. The average moisture content of the test samples at this stage was 12%. The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined by a three-point bending test according to ISO 13061–3:2014 and ISO 13061–4:2014 standards [31,32]. After these tests were completed, samples were taken from undamaged portions to determine density for estimating the relationship between bending and density.

Compression parallel to the grain was performed in a 100 kN universal testing machine (AG-I, Shimazdu, Japan). The displacement was measured using strain gage (FLAB 511, TML, Japan) with a gage factor of 2.1% ± 1%. Compression strength and Young's modulus were determined according to ISO 13061–17:2017 and ISO 130614:2014 standards [32,33].

2.4. Statistical Analysis

The statistical analysis involved a completely randomized design. ANOVA was used to test for differences in the outcomes of experiments with different numbers of samples. Averages were compared using Tukey's test. The Mann–Whitney U test was also used to test for differences between clone in terms of their physical and mechanical properties. The significance level in all tests was $p < 0.05$.

3. Results and Discussion

3.1. Moisture Content and Basic Density

The equilibrium air-dry moisture content of seven clones is described in Figure 2. As shown in Figure 2, X102 had the highest EMC value of the clones, whereas AA-4x had the lowest value. As presented in Table 2, the mean moisture contents of the seven clones were significantly different. Moreover, the data could be divided into two groups: the 4x genotypes in one group and the other clones in a second group. Because wood is always exposed to varying climatic conditions, defining the equilibrium moisture content (EMC) is important for the effective use of wood. Mechanical properties and shrinkage changes, which are probably the most important issues in the end-use applications of solid wood, are positively correlated with the EMC of wood [34–36]. The wood properties are related to heartwood and sap wood ratio, where the heartwood absorbs less water than sapwood [37–42]. This is same tendency with changing in EMC, which is affected by heartwood to sapwood ratio [43] as well as wood density [41,42]. The relationship between basic density and EMC in Figure 3 pointed out that basic density had a weakly correlation with EMC in this study. Thus, the ratio of heartwood-sapwood may explain the difference in EMC between clones. In previous research, triploid *Acacia* had a higher proportion of heartwood than diploid *Acacia* when the plants were of equal age (3.8 years) and from similar locations [30]. Thus, the EMC of clones may be higher when the ratio of heartwood increases. This observation was consistent with the findings of a previous study, which showed that the EMC for the heartwood of *Pinus radiata* was higher than that of its sapwood at all humidity and temperature conditions tested [43]. In further research, it will be necessary to investigate the heartwood ratio of tetraploid clones, in order to better explain the relationship between EMC and the heartwood ratio.

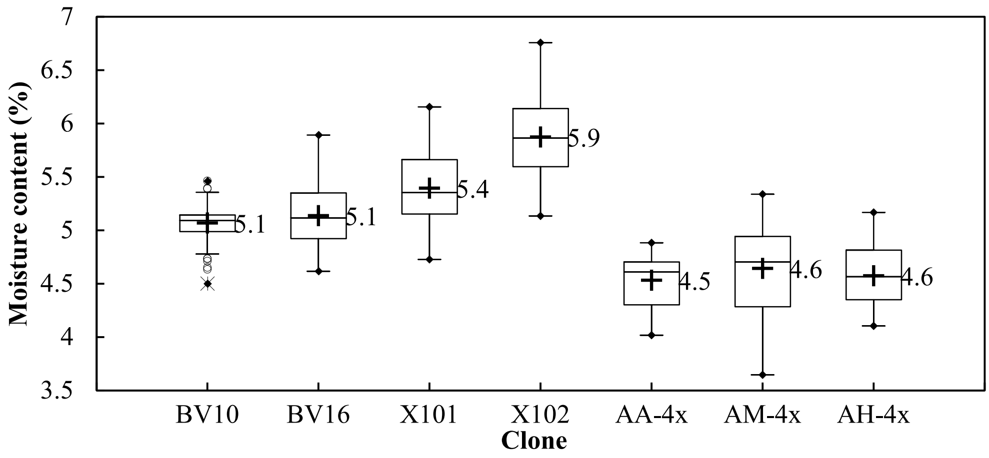

Figure 2. Variation of moisture content (%).

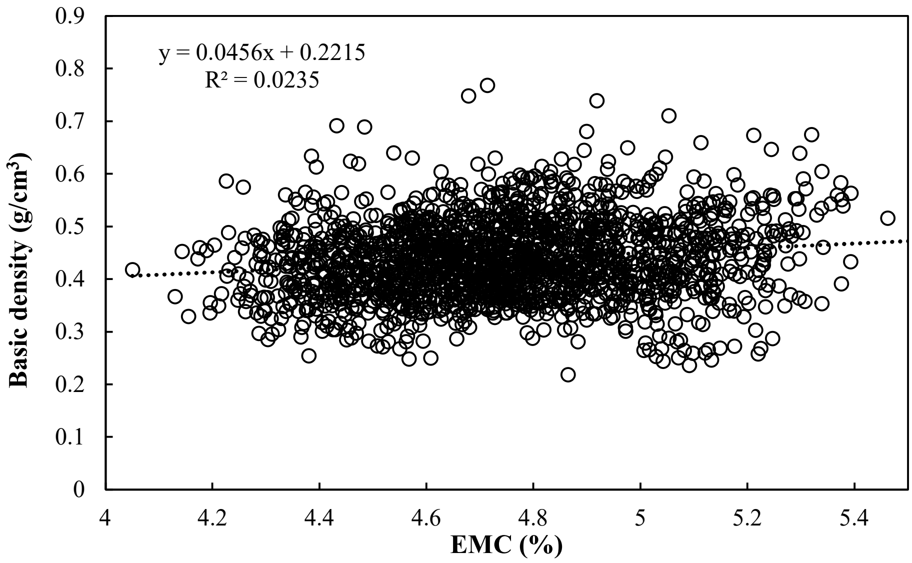

Figure 3. Relationship between basic density and equilibrium moisture content (EMC).

Figure 4 shows the basic densities of the seven clones. The clone AA-4x had the highest basic density, while AM-4x had the lowest. This result contrasts with those for EMC, where AA-4x had the lowest rather than highest value. This trend is consistent with previous studies, in which EMC was reported to decrease as basic density increased [34,35]. As shown in Table 2, the basic densities of AA-4x and AM-4x were significantly different from those of BV10 and BV16; however, the basic densities of X101, X102, and AH-4x did not differ from those of BV10 and BV16. The wood density of *Acacia* hybrids was previously reported by PV et al. [30] They showed that the basic density of diploid and triploid *Acacia* hybrids was 0.36–0.49 g/cm^3, and their mean values for diploid and triploid hybrids in southern Vietnam are consistent with our results. They also showed that *Acacia* hybrids from the same clone at the same age planted in southern Vietnam had similar basic densities. In another study, Ismail and Farawahida [7] indicated that the density of 6-year-old *Acacia* hybrids was 0.47 g/cm^3. Likewise, *Acacia* hybrids at 7–8 years old are reported to have 0.43–0.49 g/cm^3 densities [15,17]. In other studies, the densities of *Acacia* hybrids at 8 and 9–12 years old was 0.61–0.69 and 0.58 g/cm^3, respectively, whereas *A. mangium* density was 0.52 g/cm^3 and *A. auriculiformis* densities were 0.54 g/cm^3 at 5.5 years and 0.69 g/cm^3 at 11 years [44–46]. Previous research showed that a direct comparison of species is difficult because the wood density of *Acacia* species varies greatly and depends on site conditions and tree age [46]. For our study, the most interesting observation was that the basic density of AA-4x was significantly higher than that of the 2x clone.

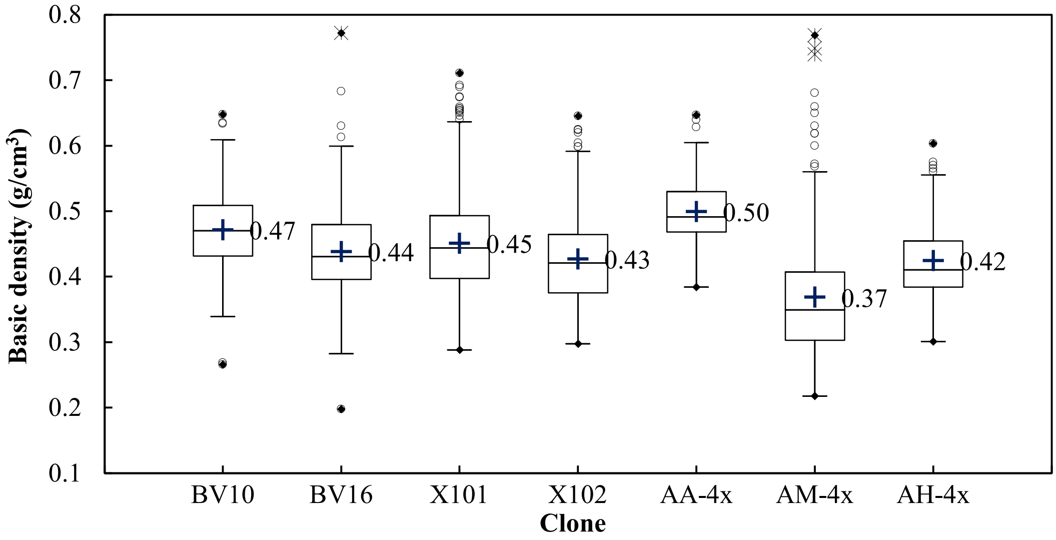

Figure 4. Variation of basic density (g/cm³).

Table 2. Wood properties and ANOVA results in different clones.

	MC (%)	BD (g/cm³)	MOR (MPa)	MOE (GPa)	σ (N/mm²)	E (GPa)
BV10	5.1 c (0.2)	0.47 b (0.06)	71 ab (17)	8.7 bc (1.1)	46.0 a (6.7)	9.6 bc (1.3)
BV16	5.1 c (0.3)	0.44 cd (0.07)	75 ab (15)	8.6 bc (0.8)	44.6 a (5.4)	9.2 c (1.5)
X101	5.4 b (0.3)	0.45 c (0.07)	79 a (14)	9.7 a (1.2)	45.3 a (5.5)	9.9 ab (1.3)
X102	5.9 a (0.4)	0.43 d (0.07)	70 b (12)	8.5 bc (1.3)	44.4 a (5.8)	9.3 c (1.3)
AA-4x	4.5 d (0.2)	0.50 a (0.05)	72 ab (11)	8.2 c (1.2)	44.0 a (6.0)	8.9 cd (1.7)
AM-4x	4.6 d (0.4)	0.37 e (0.10)	56 c (11)	7.2 d (0.9)	38.1 b (5.6)	8.2 d (1.3)
AH-4x	4.6 d (0.3)	0.42 d (0.06)	71 ab (11)	9.2 ab (0.9)	46.5 a (3.8)	10.3 a (1.0)

Data are show as mean with different group in letters; values in parentheses represent for standard deviation. MC, moisture content; BD, basic density; MOR, module of rupture; MOE, module of elasticity; σ, ultimate stress in compression parallel to the grain; E, Young's modulus in compression parallel to the grain.

The mean DBHs and tree heights are shown in Table 1. As shown, X101 was the tallest tree and AM-4x had the largest DBH. In addition, X101 and AM-4x had higher stem volumes than those of other clones. Furthermore, X101 and X102 showed higher growth than BV10 and BV16. Nonetheless, faster growth does not affect wood density, because a relationship between wood density and growth rate has not been found [47,48]. This trend is applicable to *Acacia* hybrids, as shown in a similar study of diploid and triploid hybrids [30].

The radial variation of basic density at each stem height is shown in Figure 5. The basic density increased from pith to the bark in the seven clones, which is consistent with the findings of Walker [49], Kim et al. [18], and Machado et al. [50], who reported that the specific gravity of *Acacia* increased from the pith to the outer region near the bark. Variance in this condition may be affected by variability inside the trees and other factors, such as climate conditions, during tree growth [50]. The axial variation of the basic density is presented in Figure 6. The basic density was highest at the stump, and it tended to initially decline moving up the tree, before increasing again toward the top.

Similarly, recent studies have indicated that density decreases above breast height to about the middle of the tree before increasing toward the top [18,51].

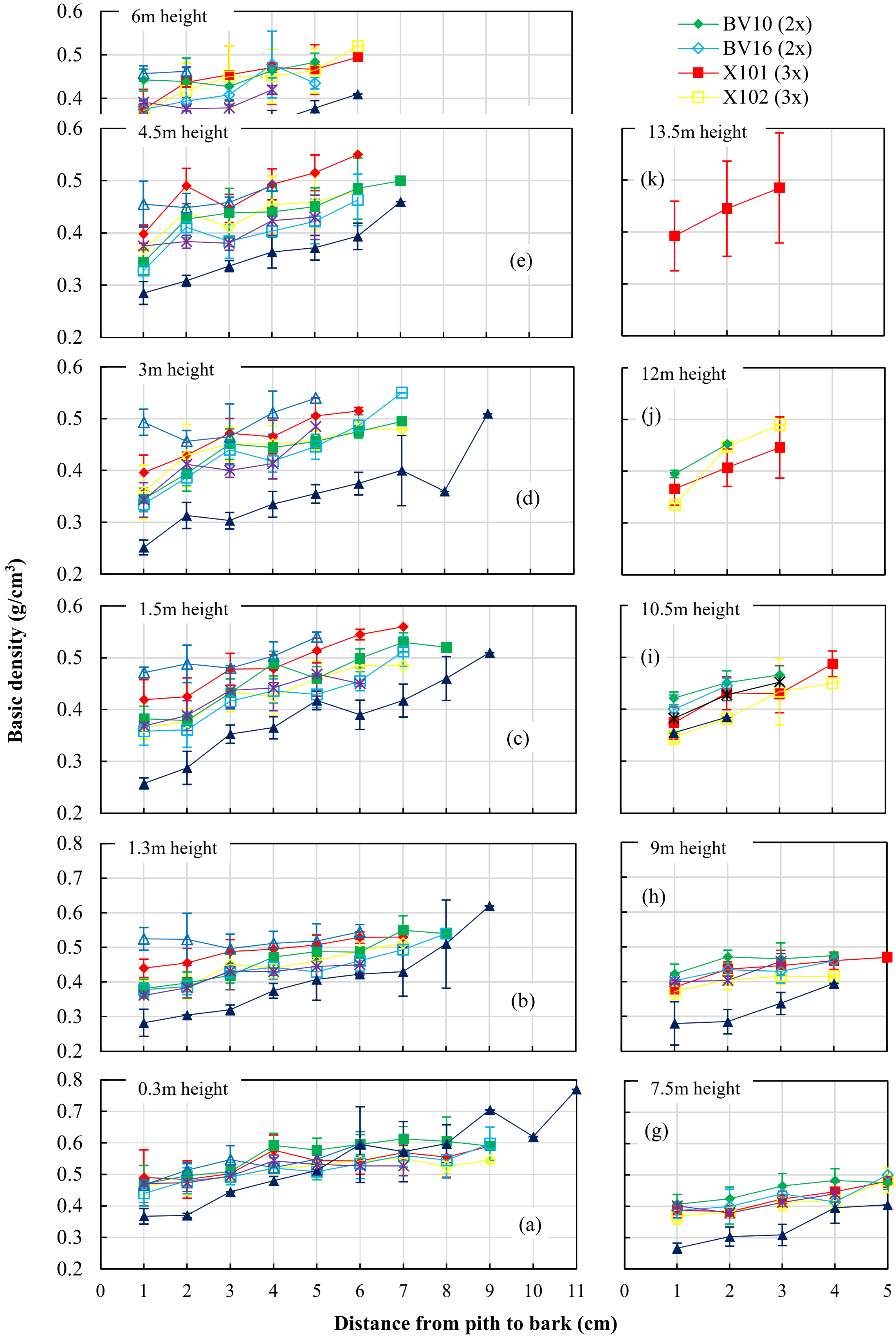

Figure 5. Basic density in the radial direction at different stem heights (bars show standard deviations).

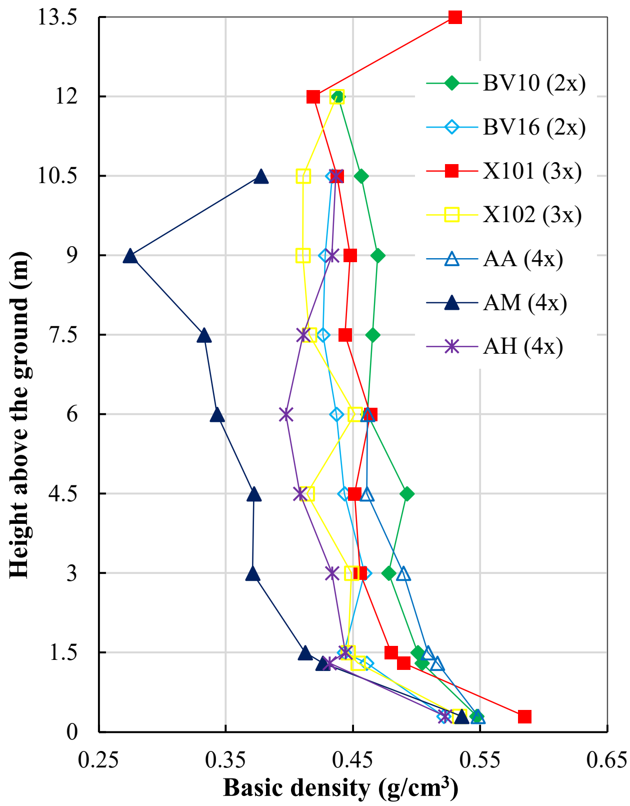

Figure 6. Profile of basic density in the axial direction.

3.2. Bending Test

Figure 7 shows the results for MOR in the different clones. The X101 clone had the highest mean MOR at 78.8 MPa, whereas the AM-4x had the lowest value at 56.2 MPa. As shown in Table 2, there was a significant difference between the MOR of X101 and AM-4x and those of the control clones BV10 and BV16.

The MOE of the seven clones is shown in Figure 8. As shown, X101 had the highest MOE at 9.7 GPa, whereas AM-4x had the lowest MOE at 7.2 GPa. Table 2 indicates that the difference between the MOE of X101 and that of the control clones was significant. Taken together, the results of the bending test suggest that the MOR and MOE of clone X101 were significantly higher than that of the control clones. However, the bending properties of AM-4x were considerably lower than those of the controls.

The MOR and MOE values from the static bending test in the present study are lower than those reported by Rokeya et al. [16], Jusoh et al. [15], and Sharma et al. [17] This inconsistency may be explained by variations in age, genotype, or location condition in our study and the others [46,47]. Figures 9 and 10 show the relationships of density with MOR and MOE, respectively. Contrary to expectations, we did not find a significant correlation between bending properties and density. This finding differs from previous studies, which have suggested that density is strongly correlated with bending properties [45,47]. These differences may be explained in part by the relationship between strength and anatomical properties. For example, Nakada et al. [52] and Zhu et al. [53] reported that strength may be related to the microfibril angle of wood fibers to which wood density is less sensitive [52,53]. The reasoning here is that density increases while microfibril angle decreases with age; this impacts mechanical tests and results in weak correlations when density alone is measured [54–56]. Grain angle has also been found to affect the correlation between density and mechanical properties [57].

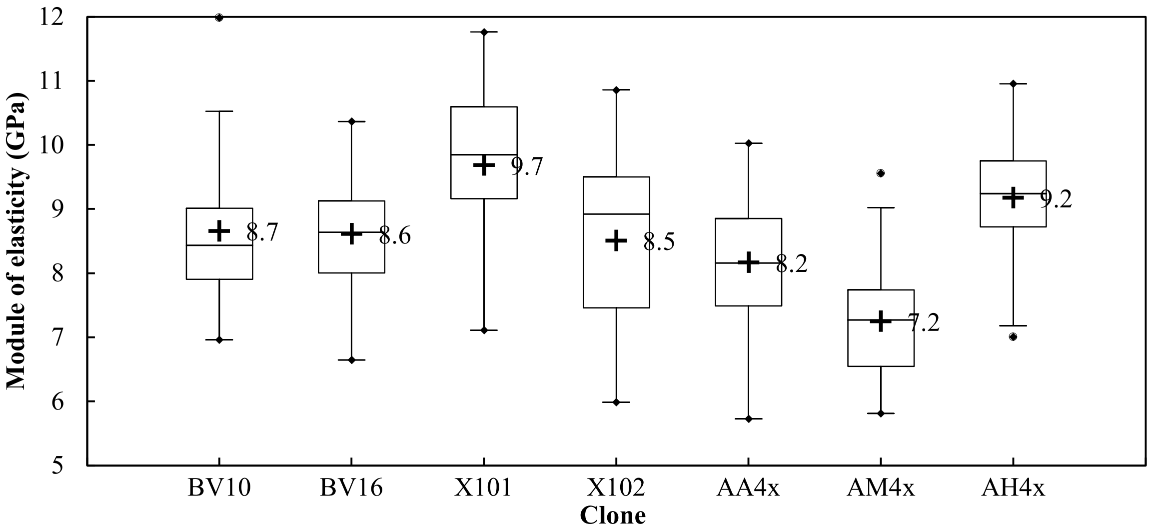

Figure 7. Variation of module of rupture (MPa).

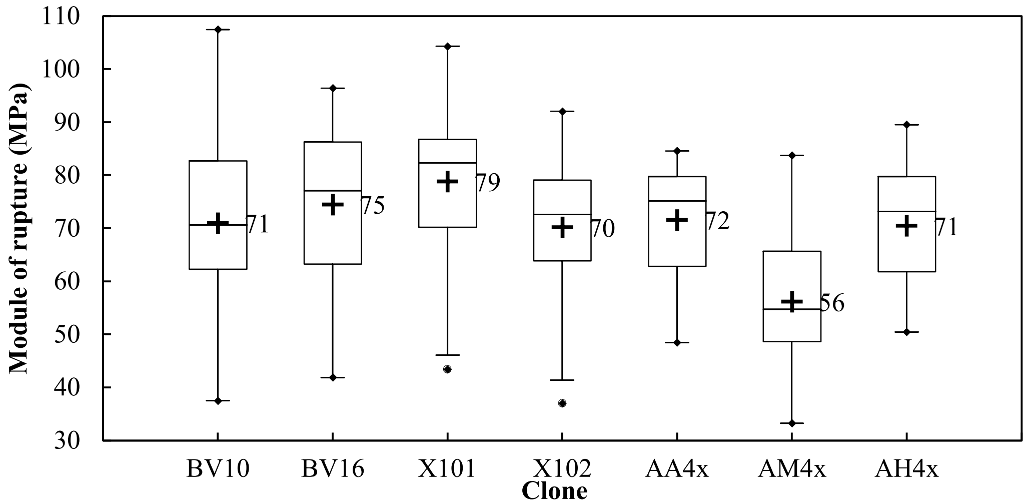

Figure 8. Variation of module of elasticity (GPa).

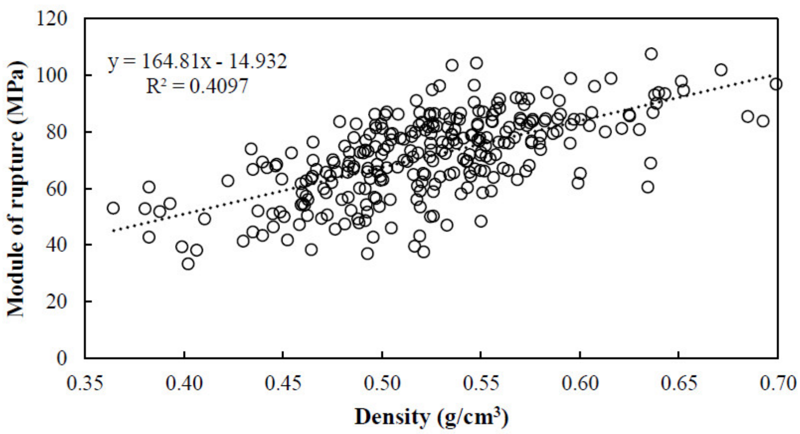

Figure 9. Relationship between module of rupture and density.

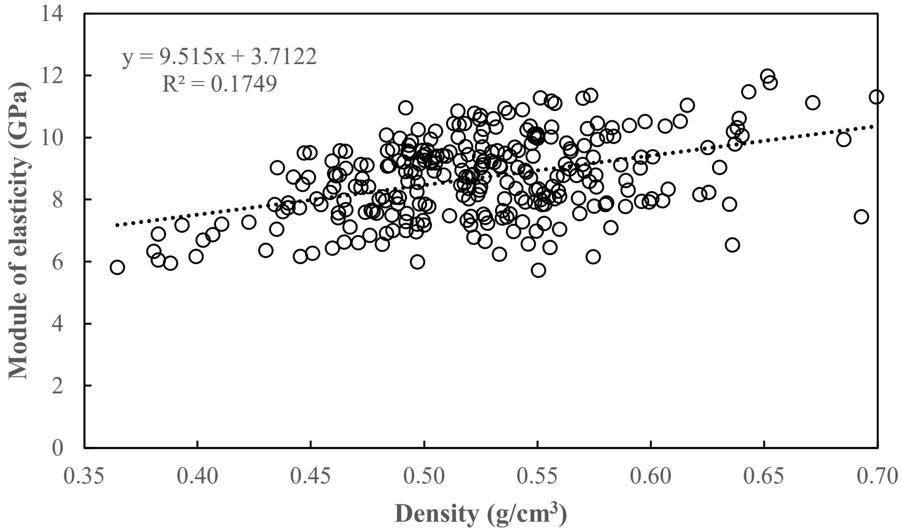

Figure 10. Relationship between module of elasticity and density.

3.3. Compression Test

Ultimate stress and Young's modulus in the compression test are shown in Figures 11 and 12, respectively. For both compression properties, AH-4x had the highest values, while AM-4x had the lowest. There was a significant difference in the stress value between AM-4x and the control clones. Likewise, the Young's modulus of AM-4x was significantly lower than that of the diploid group, whereas that of AH-4x was considerably higher than the values of the control group (Table 2). This result suggests that other triploid and the tetraploid clones have similar compression strengths to the control. By comparison, the stress values observed in the present study were not different from those of 8-year-old *Acacia* hybrids [17], but lower than those of *Acacia* hybrids at 6–7 years [7,15].

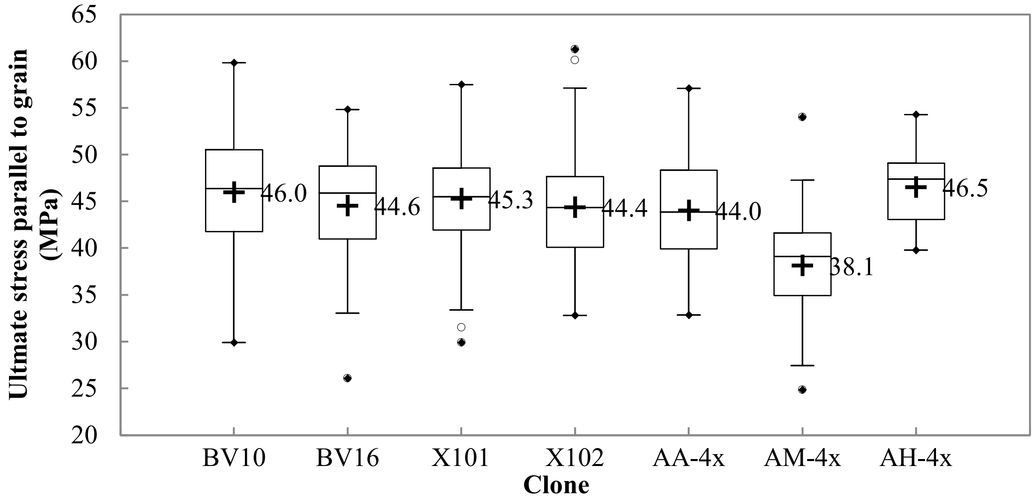

Figure 11. Variation of ultimate stress in compression parallel to the grain (MPa).

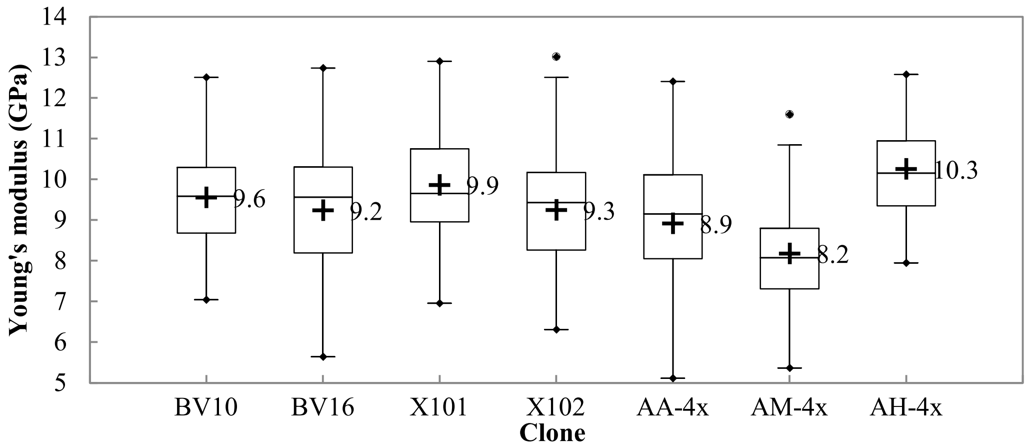

Figure 12. Variation of Young's modulus in compression parallel to the grain (GPa).

In the *Acacia* breeding program in Vietnam, there has been a focus on increasing stem volume and growth rate [3,8,21,44,58]. Improving wood quality, however, should also be an important consideration in new breeding generations. Furthermore, developing improved clones of the *Acacia* hybrid with increased properties of strength would be useful, since the hybrid suffers related problems in some extreme conditions in Vietnam [44]. Previous research suggested that the hybrid clones from Vietnam had lower densities and mechanical properties than *A. auriculiformis*, or were intermediate between their parents' characteristics [14,18]. However, according to our data, the triploid clone X101 had a similar basic density, similar compression test values, and higher bending test properties than those of diploid clones. Thus, this clone could be considered as a choice for improved *Acacia* wood quality.

It should be noted that some variation in physical and mechanical properties was unexplained by the measured factors. For instance, the effect of different site conditions and anatomical characteristics on the clone will require additional attention in further research.

4. Conclusions

Considering wood density, strength, and compression properties will be important for the improvement of the polyploid *Acacia* breeding program. Various clones had various advantages and disadvantages in this study. For example, AA-4x had significantly higher wood density than the other clones, while AM-4x had greater stem volume than the control clones. In addition, X101 had higher stem volume and bending properties (MOR and MOE) than the other clones, and similar wood density to the control. In general, triploid and tetraploid *Acacia* hybrids have the potential to be alternative species to supply *Acacia* wood as valuable hardwood timber. Moreover, X101 could potentially be used for selection to improve and increase the production of high-quality *Acacia* wood.

Author Contributions: D.D.V. wrote the first draft of the manuscript, implemented the experiment and analyzed the data. T.M., T.I., N.T.K., N.Q.C., and S.T. designed the experiment, and reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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