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ORIGINAL ARTICLE

Variation in intrinsic wood properties of *Melia azedarach* L. planted in northern Vietnam

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Abstract Variations in intrinsic wood properties [growth ring width (GRW), specific gravity (SG), fiber length (FL), and microfibril angle (MFA)] of 17–19-year-old *Melia azedarach* trees grown in two sites in northern Vietnam were investigated for effective utilization of the wood. Five discs were collected at 0.3-, 1.3-, 3.3-, 5.3-, and 7.3-m heights above the ground. The estimated mean GRW, SG, FL, and MFA were 7.44 mm, 0.548, 1.07 mm, and 14.65°, respectively. There were significant ($P < 0.05$) differences among trees and between sites in SG, FL, and MFA. Longitudinal position significantly ($P < 0.05$) influenced GRW and SG. Radial position was highly ($P < 0.001$) significant to all the wood properties and contributed the highest (GRW: 52.58%, SG: 58.49%, FL: 77.83%, and MFA: 26.20%) of the total variations. FL and SG increased from pith to bark, while GRW and MFA decreased from pith to bark. Fiber length increment (FLI) tends to stabilize between 7th and 10th rings. This should be taken into account when processing logs. The results of this study, therefore, provide a basis for determining management strategies appropriate to structural timber production of *M. azedarach* plantation trees in northern Vietnam.

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Keywords *Melia azedarach* · Growth ring width · Specific gravity · Fiber length · Microfibril angle

Introduction

Melia azedarach L. is a deciduous tree belonging to the family of Meliaceae. It is native to the Himalaya region of Asia [1]. The species is well adapted to warm climates, poor soils, and seasonally dry conditions [2]. The fully grown tree has a rounded crown, and commonly measures 7–12-m tall. However, in exceptional circumstances, *M. azedarach* can attain a height of 45 m. The leaves are up to 50-cm-long, alternate, long-petioled, two or three times compound (odd-pinnate); the leaflets are dark green above and lighter green below, with serrate margins. The flowers are small and fragrant, with five pale purple or lilac petals, growing in clusters. The fruit is a drupe, marble-sized, light yellow at maturity, hanging on the tree all winter, and gradually becoming wrinkled and almost white [3].

The main utility of *M. azedarach* is its high-quality timber. Seasoning is relatively simple in that planks which dry without cracking or warping and are resistant to fungal infection. The wood is used to manufacture agricultural implements, furniture, plywood, boxes, poles, and tool handles [1]. It is also used in cabinet making as well as in construction [4]. Besides, *M. azedarach* is a multi-purpose tree species. Its leaves can be used as green manure and insecticides. It is often planted for fuel supply in Middle East and in Assam (India), where it is grown on tea estates for fuel [1]. In Vietnam, most of the *M. azedarach* were planted in short rotation around 5–6 years with the purpose to supply raw material for pulp and particleboard industries.

Wood property knowledge is of great importance in the quality improvement of various wood products [5]. An examination of literature reveals that wood properties are highly variable. They vary from stand to stand, tree-to-tree, around the circumference, across the radius, along the height, and even within small sampling unit like growth ring [6]. Although these variations provide great potential for sustainable utilization of wood, there is no information about wood properties of *M. azedarach* grown in Vietnam. Thus, no effort has been made to investigate the variation in wood properties of *M. azedarach* in Vietnam, despite the importance of this species and the multiuse of its wood. Therefore, this study was carried out to investigate variations in wood properties (growth ring width, specific gravity, fiber length, and microfibril angle) within tree, between trees, and between sites of *M. azedarach* trees grown in northern Vietnam. Information gained provide basis for determining management strategies appropriate for sustainable wood utilization of *M. azedarach* trees growing in northern Vietnam.

Materials and methods

Study site and sampling

Samples were collected from two *M. azedarach* state-owned plantations in Vietnam. The location and detailed information of the two sites are given in Table 1. The trees were around 17–19 years old (ring count at 15 cm above the ground). The trees were planted at a density of 830 trees per hectare at spacing of 4 m × 3 m from seedlings produced by seeds from natural forests located near each site. The anticipated rotational age of this species is approximately 15–20 years. Thinning was carried out at the ages of 3 and 6 (removing 50% of standing trees each time). The thinned trees were used as poles, while the branches were used as firewood. In August 2016, six trees (three from each plantation) were harvested. The trees were chosen based on straightness, normal branching, and no signs of any diseases or pest symptoms. The trees were felled through cutting their stems at 15 cm above the ground. Diameter at breast height (1.3 m above the ground) as well as the total stem height for each tree were measured just before felling (Table 2).

Table 1 General characteristics of the study sites

Description	Site 1 Northeast	Site 2 Northwest
Province	Tuyen Quang	Son La
Latitude	22°17′01″N	20°56′18″N
Longitude	105°19′22″E	104°26′25″E
Altitude (m)	112	434
Mean rainfall (mm year^{-1})	2000	1300
Mean temperature (°C)	23.4	24
Soil origin	Calcisols	Ferralsols

Wood specimen preparation

Cross-sectional discs of 3 cm thickness from each tree were cut at different heights (0.3, 1.3, 3.3, 5.3, and 7.3 m heights above the ground) to examine growth ring width (GRW) and specific gravity (SG). A 3-cm-thick disc was also collected from each tree at the height of 1.3 m for measurement of fiber length (FL) and microfibril angle (MFA) of S_2 layer of cell wall.

GRW

Pith-to-bark strips [Radius × 30 (Tangential) × 15 (Longitudinal) mm] from the south side were cut from the discs and air-dried. Thus, the strips were conditioned in a room at a constant temperature (20 °C) and relative humidity (60%) to constant weight. With the same strips, images were taken using a Canon MP-650 scanner attached to a computer. GRW was measured using Image J Software. GRW of each tree was expressed as a mean value of all individual rings in that tree.

SG

Due to distinct growth rings (Fig. 1), after measuring the GRW, the same strips were then cut into individual rings for measurement of SG in air-dry. Two or more rings were combined in some positions where the rings were too small to be measured. SG, which is the ratio of the density of a wood to that of water at 4 °C [7], was measured by an electronic densimeter MD-300S. Measurement time per sample was about 10 s.

FL and MFA

Pith-to-bark strips [Radius × 20 (T) × 10 (L) mm] were cut from discs cut at 1.3 m for measuring FL and MFA.

Table 2 Age, diameter at breast height, and total stem height of sampled *Melia azedarach* trees

Site	Tree no.	Age[a] (years)	DBH (cm)	H (m)
Site 1	1	18	32.5	19.6
	2	19	32.2	21.1
	3	17	32.5	21.4
Site 2	4	18	33.8	20.1
	5	18	32.2	19.1
	6	17	29.9	21.4

DBH diameter at breast height (at 1.3 m above the ground); *H* tree height

[a] Measured by ring counting at the 15 cm above the ground

Fig. 1 Tree ring in cross section obtained from *Melia azedarach* (at 3.3 m height, tree no. 1, and site 1)

The outermost latewoods at ring number 1, 2, 3, 5, 8, 10, 13, 15, and 17 from pith of strips were cut and macerated by dipping in 1:1 solution of 65% nitric acid (HNO_3) and distilled water (H_2O) plus potassium chlorate ($KClO_3$) (3 g/100 ml solution) for 5 days. The pieces were rinsed three times with distilled water, stained with safranin, and then mounted on a glass slide. The FL of 30 fibers was measured by using a Nikon V-12 profile projector at a 50-fold magnification.

Small blocks (10 (R) × 10 (T) × 10 (L) mm) at ring number 1, 2, 5, 10, and 15 were also prepared from the strips. Radial sections of 8 μm thickness were cut by microtome, macerated (using the solution described above) for 40 min, and cleaned in distilled water. The sections were dehydrated in 10% ethanol, and subsequently in an ethanol series of 30, 60, 80, and 100% ethanol for 5 min each. The sections were then placed on a slide glass and immersed in a 3% solution of iodine–potassium for 2–5 s. One or two drops of 60% HNO_3 were added and a coverslip was placed over the wetted specimen. MFA of 25 fibers per small block was measured by Microscope and Image J software.

Determination of fiber length increment (FLI)

Variations in length of wood fibers were approximated by a logarithmic relationship to the annual ring from the pith. The FLI was calculated using the procedure described by Honjo et al. [8]. The FLI annually (from ring to ring) was determined using the following formula:

$$\mathrm{FLI} = \frac{\Delta \mathrm{FL}}{\Delta \mathrm{RN}},$$

where: FLI is the fiber length increment; ΔFL is the change in fiber length; and ΔRN is the change in ring number. The FLI was then expressed as a percentage.

Statistical analysis

Analysis of variance (ANOVA) for all wood properties (GRW, SG, FL, and MFA) was performed according to the model shown in Table 3 to test the significance of site, tree, height level, and radial position effects. Trees were considered as random effects, and the other sources of variation as fixed effects. Variance components for the sources of variation were also estimated. Statistical analysis was performed using R software version 3.2.3.

Results and discussion

GRW

The GRW of *M. azedarach* was on average 7.44 mm, with an average range between trees from 6.53 to 8.64 mm (Table 4). Site and tree-to-tree within a site were not a source of variations of GRW, explaining only 0.28 and 1.58% of the total variation, respectively (Table 5). The radial variation of GRW was highly ($P < 0.001$) significant and contributed the highest (52.58%) of the total variation. Mean GRW near the pith was large and decreased rapidly with cambial age up to 5 and 6 years before being less or more stable to the bark. However, there were some fluctuations and spikes in some trees (Fig. 2).

The longitudinal variation of GRW was highly significant ($P < 0.05$) but contributed little (2.67%) to the total variation (Table 5). Mean GRW decreased with height level ranged from 8.70 to 6.34 mm.

The findings of the present study are in agreement to those in literature. Matsumura et al. [9] reported wood properties and their variation in the stem of 17-year-old *M. azedarach* trees grown in Japan. It was found that GRW near the pith up to 3-m height above the ground was large and became stable beyond the fourth ring regardless of stem height. GRW is highly variable as it is controlled by a

Table 3 Model used in the analysis of variance

No.	Source of variation
1	Site (S)
2	Tree/site (T/S)
3[a]	Height level (L)
4[a]	L × S
5[a]	L × T/S
6	Radial position (P)
7	P × S
8	P × T/S
9[a]	P × L
10[a]	P × L × S
11	R/P/L/T/S

[a] Source of variations excluded in fiber length and microfibril angle analysis, since wood specimen was collected at 1.3-m stem height only

Table 4 Mean values per site and tree for selected wood properties of *Melia azedarach*

Category	Growth ring width (mm)	Specific gravity	Fiber length (mm)	Microfibril angle (°)
Tree no.				
1	8.13 ± 0.63^{a}	0.536 ± 0.008^{bc}	1.05 ± 0.01^{c}	16.86 ± 0.28^{a}
2	6.53 ± 0.62^{a}	0.548 ± 0.008^{b}	1.03 ± 0.01^{c}	15.56 ± 0.30^{b}
3	8.64 ± 0.55^{a}	0.523 ± 0.008^{c}	0.98 ± 0.01^{d}	15.95 ± 0.31^{b}
4	6.76 ± 0.74^{a}	0.572 ± 0.008^{a}	1.15 ± 0.01^{a}	13.70 ± 0.23^{c}
5	7.57 ± 0.34^{a}	0.548 ± 0.006^{b}	1.10 ± 0.01^{b}	13.23 ± 0.23^{cd}
6	7.11 ± 0.49^{a}	0.557 ± 0.008^{ab}	1.10 ± 0.01^{b}	12.58 ± 0.25^{d}
Site				
1	7.73 ± 0.35^{a}	0.536 ± 0.005^{b}	1.02 ± 0.01^{b}	16.12 ± 0.17^{a}
2	7.15 ± 0.32^{a}	0.559 ± 0.004^{a}	1.12 ± 0.01^{a}	13.17 ± 0.14^{b}
Mean	7.44 ± 0.24	0.548 ± 0.003	1.07 ± 0.01	14.65 ± 0.12

Mean values are followed by standard errors

^{a,b,c,d} Means with different superscript within a column significantly differ ($P < 0.05$)

Table 5 Variance components for growth ring width and specific gravity of *Melia azedarach*

Source of variation	*df*	Growth ring width		Specific gravity	
		P value	Var (%)	*P* value	Var (%)
Site (S)	1	0.226	0.28	0.001	2.49
Tree/site (T/S)	4	0.085	1.58	0.033	1.97
Height level (L)	4	0.008	2.67	0.001	4.92
L × S	4	0.673	0.45	0.055	1.67
L × T/S	16	0.994	1.02	0.001	6.66
Radial position (P)	18	0.001	52.58	0.001	58.49
P × S	17	0.001	5.11	0.013	2.50
P × T/S	66	0.001	14.37	0.011	6.78
P × L	69	0.880	5.06	0.100	2.59
P × L × S	68	0.520	5.54	0.100	2.61
R/P/L/T/S	250		11.34		9.33

df degrees of freedom, *Var* variance (%)

variety of factors such as environmental fluctuations [7]. Beside, plant spacing is also a factor that can influence GRW. There is acceleration of growth for widely spaced trees than crowded trees, because widely spaced trees do not compete for growth elements such as nutrients, water, and sunlight, and hence, they tend to have wider GRW [10]. In the present study, plant spacing was the same for two sites, and hence, no significant ($P > 0.05$) difference was observed on mean GRW between the sites.

SG

The results on wood SG of *M. azedarach* are presented in Tables 4 and 5, and Figs. 3 and 4. Site, tree-to-tree within the site, stem height position, and radial position significantly ($P < 0.05$) affected wood SG of *M. azedarach*. However, radial position contributed the highest (58.49%) to the total variation. The wood SG values of *M. azedarach* found in the present study ranged from 0.523 to 0.572 between trees. This is in agreement to the values in the literature. Richter and Dallwitz [11] reported an SG of 0.5–0.65 of *M. azedarach*. On the other hand, Trianoski et al. [12] and El-Juhany [1] reported lower values, 0.49 and 0.404–0.413, respectively. The variation between different reports of wood SG of the same species may be attributed to age factor [1] and to effects of geographic variation such as latitude, temperature, and precipitation [13]. In the present study, the differences in altitude, mean annual rainfall, and soil types between the two sites (Table 1) may have influenced the variation of wood SG of *M. azedarach*.

Wood SG in *M. azedarach* increased from pith to bark (Fig. 3). The pattern was the same at all stem height levels. The findings of the present study are in agreement to those in literature [1, 9, 14]. This pattern was also seen in other species which belong to Meliaceae family such as *Toona ciliata* [14] and *Swietenia macrophylla* [15]. On the other hand, Wahyudi et al. [16] reported a nearly constant basic density of *Azadirachta excelsa* from pith to bark. Beside, Ofori and Brentuo [17] showed that the density of *Cedrela odorata* was low at the pith, increased rapidly outwards to a peak, and declined steadily towards the periphery in the radial direction. Based on the present results and previous reports, radial variation of wood SG depends on species.

There were significant ($P < 0.05$) differences on SG among different height levels with the general trend decreasing from 0.3 to 3.3 m before slight increasing to the top (Fig. 3). The results are consistent with the results of Kim et al. [18] who reported the SG at the stump was the highest, tending to decrease and then increase toward the top on *Acacia mangium* and *Acacia auriculiformis* planted

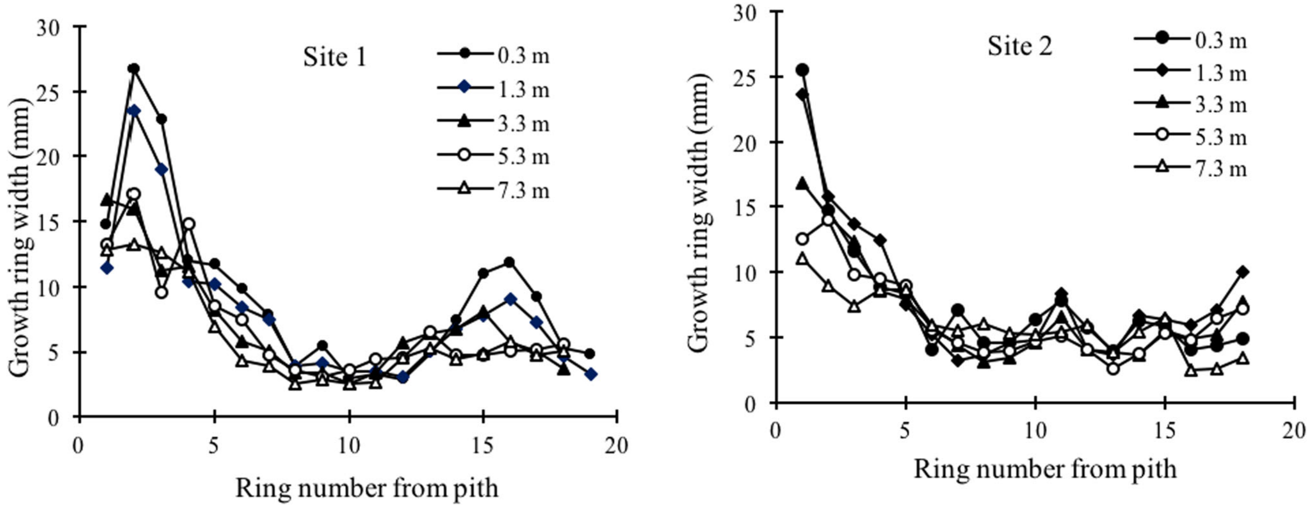

Fig. 2 Variation of growth ring width in the radial and vertical directions of *Melia azedarach* in two sites

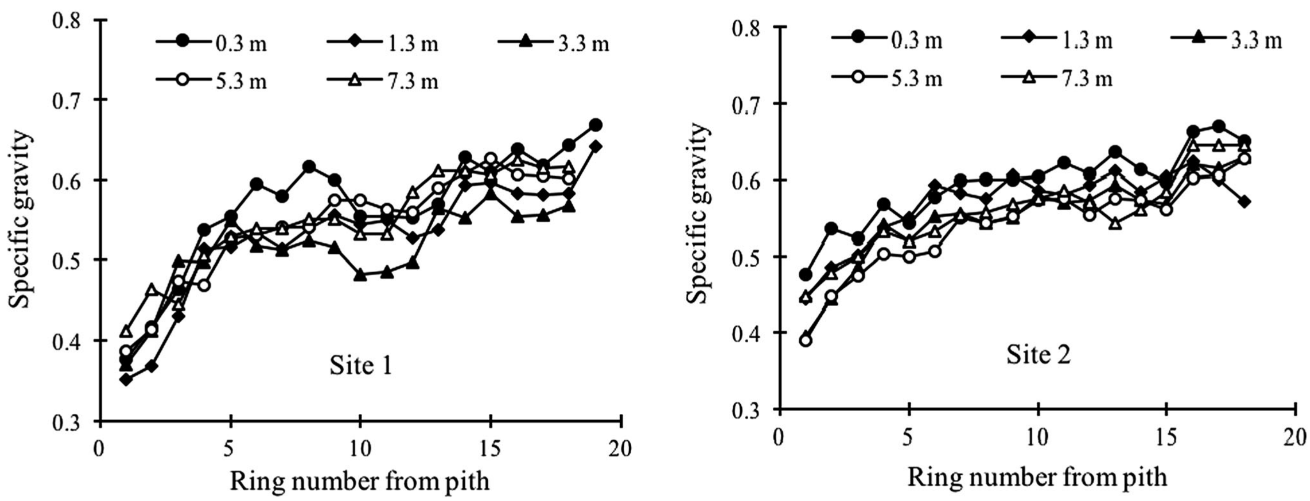

Fig. 3 Variation of specific gravity in the radial and vertical directions of *Melia azedarach* in two sites

Fig. 4 Tree stem maps showing variations in growth ring width and specific gravity. Each graph represents one tree from each site. *Light* and *dark colors* signify low and high specific gravity, respectively

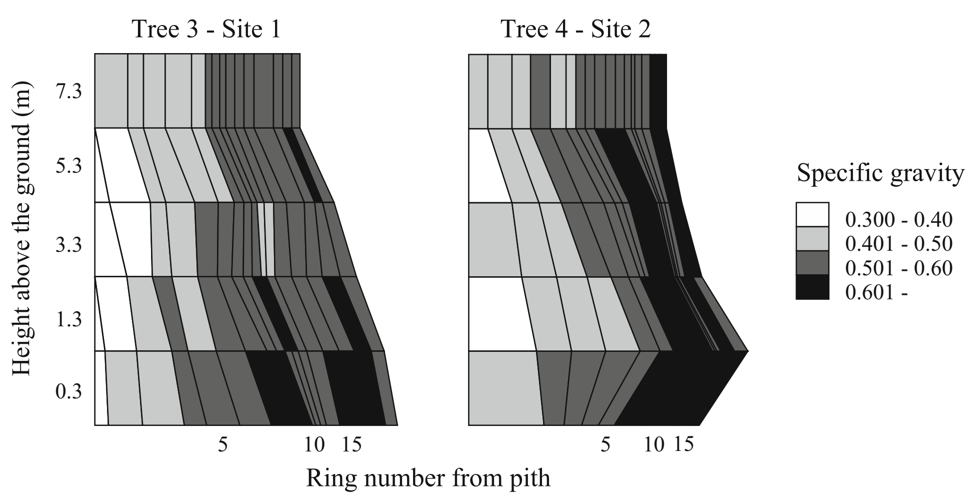

Table 6 Variance components for fiber length and microfibril angle of *Melia azedarach*

Source of variation	*df*	Fiber length		*df*	Microfibril angle	
		P value	Var (%)		*P* value	Var (%)
Site (S)	1	0.001	5.66	1	0.001	19.15
Tree/site (T/S)	4	0.001	1.68	4	0.001	2.23
Radial position (P)	8	0.001	77.83	4	0.001	26.20
P × S	8	0.001	1.02	4	0.001	1.96
P × T/S	32	0.001	0.70	16	0.001	4.61
R/P/T/S	1566		13.12	720		45.86

df degrees of freedom, *Var* variance (%)

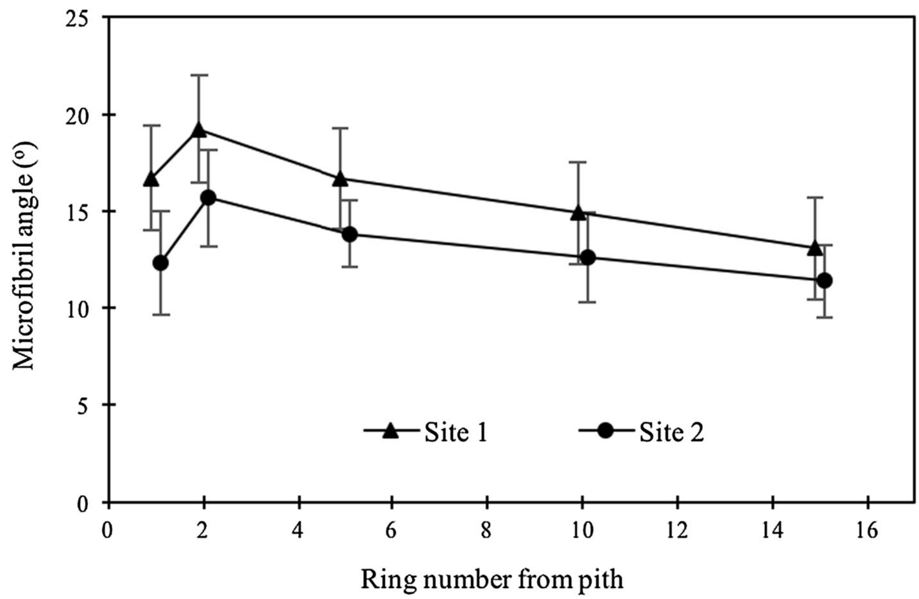

Fig. 5 Radial variation of MFA for two different sites of *Melia azedarach* (*Bars* mean standard deviation)

in northern Vietnam. In agreement with Matsumura et al. [9], Fig. 4 showed that there were low and high SG zones in the stem with the high SG zone exists in the outer area of the stem and a low SG zone in the inner area.

MFA

A summary of the results on MFA of S_2 layer in cell wall of wood fiber of *M. azedarach* is presented in Tables 4 and 6. The results indicate that there were significant ($P < 0.001$) differences on MFA between sites, among trees, and along the radial direction. The most important and highly significance source of variation was radial position, explaining 26.20% of the total variation. Mean MFA followed a declining trend from pith to bark (Fig. 5). The phenotypic trends observed for MFA were consistent with the previous reports in *M. azedarach* [9] and other species [19, 20]. High MFA in rings close to the pith ensure flexibility and protect the young shoots from wind damage.

FL

FL results of *M. azedarach* are summarized in Tables 4 and 6. Mean FL was 1.07 mm, varying between trees from 0.98 to 1.15 mm. Site, tree-to-tree within site, and radial position were significant sources of variation in FL of *M. azedarach*. However, radial position contributed the highest (77.83%) to the total variation. FL at breast height showed an increase from pith to bark (Fig. 6). Radial increase in FL from pith to bark is due to increase in length with cambial age [9].

The length of fibers in the present study is in agreement to those in literature. Abdul [21] reported a 0.78–1.3 mm length for *M. azedarach* fibers, while Richter and Dallwitz [11] reported an average FL of 0.8–1.65 mm. Contrary, El-Juhany [1] reported a lower average FL of 0.742–0.792 mm for 8-year-old *M. azedarach*. The significant variation between trees in FL in the present study agrees with that reported in *M. azedarach* [1] and *Quercus suber* L. [22]. However, other researchers reported a small

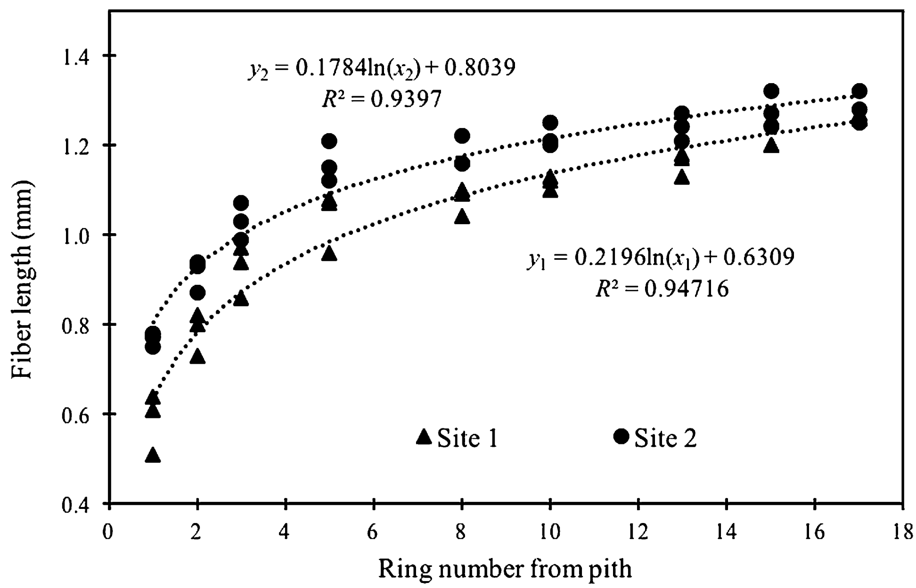

Fig. 6 Radial variation of fiber length for two different sites of *Melia azedarach*

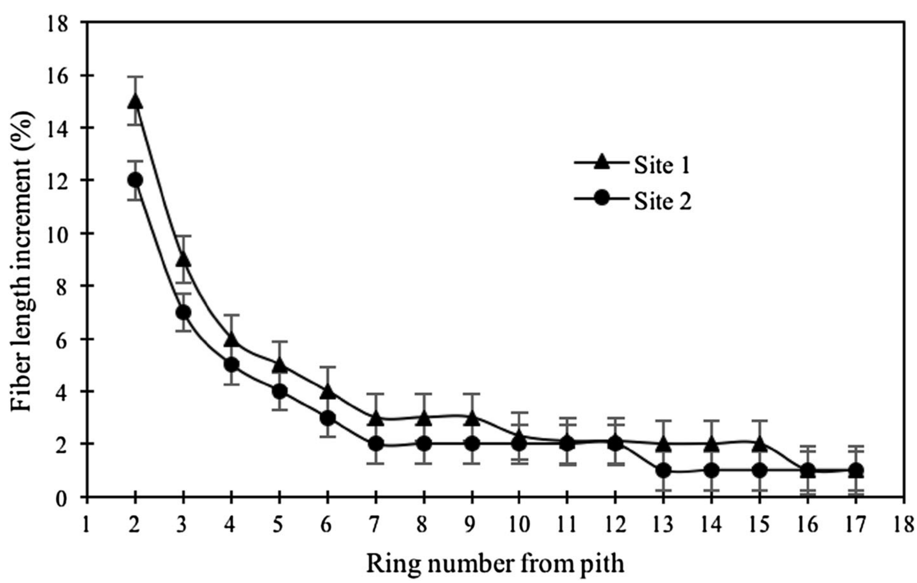

Fig. 7 Fiber length increment with cambial age of *Melia azedarach* in Vietnam (*Bars* mean standard error)

variation in FL among trees [23]. Tree-to-tree variation in FL among trees could be attributed to the inherent potential of individual trees to produce longer or shorter fibers than their neighbours [1].

Stabilizing point of FLI

FL for site 1 and site 2 was regressed logarithmically (Fig. 6). Figure 6 shows that the radial pattern of FL of the studied trees from site 1 and site 2 could be calculated using the following functions: $y_1 = 0.2196 \ln(x_1) + 0.6309$ and $y_2 = 0.1784 \ln(x_2) + 0.8039$, respectively. Then, FLI in percentage for each ring number for the sites was estimated and plotted (Fig. 7). Figure 7 shows that FLI started stabilizing between 7th and 10th rings for both sites. This indicates that wood beyond 7th ring consists of comparative long fibers.

Implications for wood utilization of *M. azedarach* in Vietnam

The length of fibers in wood is essential for the optimization of timber utilization, quality, and value of final products [24]. Mature wood with long FL, high SG, and low MFA is preferred for structural purposes [24–26]. In the present study, FL increased from pith to bark (Fig. 6) and wood beyond ring number 7 from the pith consists of comparatively long fibers, high SG, and low MFA.

Therefore, wood from ring number 7 to the bark could be used for structural purposes. In addition, *M. azedarach* trees planted in site 2 (Son La provenance) had higher SG, longer FL, and lower MFA than trees planted in site 1 (Tuyen Quang provenance). This implies that site 2 or any other location with similar environmental conditions (soil, rainfall, temperature and altitude) to site 2 should be preferred for establishment of *M. azedarach* plantations in northern Vietnam. However, further study is required to determine the mechanical properties for fully sustainable wood utilization of *M. azedarach* in northern Vietnam.

Conclusions

The results of the study showed a significant variation among trees and between sites in wood SG, FL, and MFA. *M. azedarach* trees grown in site 2 provenance were superior in wood SG, FL, and MFA. There were no significant differences among trees and between sites in GRW of *M. azedarach* trees. Longitudinal position significantly influenced GRW and wood SG. Mean GRW decreased with increasing stem height, while wood SG decreased from the stump to intermediate stem before slight increasing to the top. Radial position was highly significant to all wood properties and contributed the highest of the total variation. FL and wood SG increased from pith to bark, while GRW and MFA decreased from pith to bark. FLI stabilizes beyond ring number 7 from the pith. This should be taken into account when processing logs of *M. azedarach* trees in northern Vietnam.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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