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Anatomical characteristics and wood properties of unutilized *Artocarpus* species found in secondary forests regenerated after shifting cultivation in Central Kalimantan, Indonesia

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Abstract The anatomical characteristics and wood properties of *Artocarpus* species naturally regenerated in secondary forests in Central Kalimantan, Indonesia, were investigated to determine their usefulness as alternative wood resources. The following six *Artocarpus* species were used in the present study: *A. dadah*, *A. nitidus*, *A. elasticus*, *A. tamaran*, *A. anisophyllus*, and *A. odoratissimus*. The mean value of stress-wave velocity was 3.22 km s^{-1} for 12 trees from the six *Artocarpus* species. Among the six species, *A. dadah*, *A. nitidus*, and *A. odoratissimus* showed relatively higher stress-wave velocity values compared to those of other tropical commercial plantation species, indicating that the woods in these three *Artocarpus* species have higher values of Young's modulus. The mean values for the anatomical and other wood properties of the 12 trees of the six *Artocarpus* species were as follows: vessel diameter, 150 μm; vessel element length, 0.41 mm; fiber diameter, 19.8 μm; fiber wall thickness, 1.28 μm; fiber length, 1.34 mm; basic density, 0.50 g cm^{-3}; compressive strength parallel to grain at green condition, 31.2 MPa. Basic density was positively correlated with compressive strength, suggesting that the mechanical properties of *Artocarpus* species can be predicted by measuring the basic density. Based on the results, the six *Artocarpus* species used in the present study could produce solid lumber for construction, furniture, and other uses, suggesting that these species might be alternative tree species for lumber production in agroforestry in Asian countries.

Keywords Stress-wave velocity · Vessel morphology · Fiber morphology · Basic density · Compressive strength

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Introduction

In Southeast Asian countries, commercial large-scale plantation forests as well as community forests have been established with fast-growing tree species, such as *Acacia mangium*, *Falcataria moluccana* (Syn. *Paraserianthes falcataria*), *Gmelina arborea*, *Eucalyptus camaldulensis,* and others (Lemmens et al. 1995; Ishiguri et al. 2007, 2009, 2013; Yahya et al. 2010; Makino et al. 2012; Nugroho et al. 2012; Adi et al. 2015). The woods from these species have been mainly used for pulp chip and plywood productions. On the other hand, many tree species with fast-growing characteristics can be found in naturally regenerated secondary forests after shifting cultivation (Lemmens et al. 1995; Istikowati et al. 2014; Adi et al. 2015; Takeuchi et al. 2016). However, the woods from these fast-growing trees found in secondary forests are mainly used as firewood. Recently, the wood properties and anatomical characteristics have been investigated for three unutilized fast-growing tree species, *Artocarpus elasticus*, *Neolitsea latifolia*, and *Alphitonia excelsa*, which were naturally regenerated in a secondary forest in South Kalimantan, Indonesia (Istikowati et al. 2014, 2016a, b). They found that the woods from these three species could be used as pulpwood. To utilize the wood from unutilized fast-growing tree species in secondary forests, their wood properties and anatomical characteristics should be clarified.

The genus *Artocarpus* belongs to the family Moraceae, and the species are distributed from India to South Asia and the Western Pacific (Ogata et al. 2008). According to Lemmens et al. (1995), 23 *Artocarpus* species are distributed across Kalimantan Island. These species have been also selected for home garden species in many Asian countries (Gajaseni and Gajaseni 1999; Chandrashekara 2007). In addition, the fruits from *Artocarpus* species are well-known and important food sources (for example, breadfruit and jackfruit) not only for human but also wildlife, such as chimpanzees and monkeys (Lemmens et al. 1995; McLennan and Hill 2012). Although the exact tree age was unknown, Istikowati et al. (2014) reported that tree density and mean stem diameter at 1.3 m above the ground in *A. elastics* were 1000 trees 0.01 km^{-2} (1000 trees ha^{-1}) and 21.7 cm, respectively, in a 11-year-old secondary forest naturally regenerated after shifting cultivation, suggesting that *A. elastics* can be regarded as a fast-growing tree species. Therefore, if *Artocarpus* species' woods are found to be useful alternative wood resources, it is possible that *Artocarpus* species will become promising species for agroforestry or environmentally friendly forestry in the tropics.

In the present study, to determine the uses of *Artocarpus* species found in secondary forests as alternative wood resources, the anatomical characteristics and wood properties were investigated for six *Artocarpus* species naturally grown in secondary forests located in Central Kalimantan, Indonesia.

Materials and methods

Materials

The wood samples were collected from secondary forests in the concession area of PT Sari Bumi Kusuma, Central Kalimantan, Indonesia (0°44′–0°50′ S, 112°16′–112°19′ E). The secondary forests were naturally regenerated after shifting cultivation. Although the tree age was unknown, the average rotation cycle of shifting cultivation in the secondary forests was 11 years according to the local information. The wood samples were collected from 12 individual trees consisting of 4 different trees locally called the dadak, kapuak, mentawa, and pihing. Leaf specimens were also collected while gathering wood samples in order to identify the trees' botanical names. The botanical names of these 12 *Artocarpus* trees were identified by the Indonesian Institute of Sciences. Eventually, the trees were identified as six different species (Table 1).

Before collecting the wood samples, the stem diameter at 1.3 m above the ground, tree height, and stress-wave velocity of the stem were measured. The stress-wave velocity of the stem was measured using a commercial handheld stress-wave timer (Fakopp Microsecond Timer, Fakopp Enterprise) as described in our previous study (Makino et al. 2012). Start and stop sensors were set at 150 and 50 cm above the ground, respectively. The values of the stress-wave velocity of standing trees were calculated by dividing the span between the sensors (100 cm) by the stress-wave time.

Anatomical characteristics

The following anatomical characteristics were measured at 1 cm intervals from pith to bark: vessel diameter, vessel element length, fiber diameter, fiber wall thickness, and fiber length. Core samples were used for determining the anatomical characteristics. Core samples (5 mm in diameter) were taken from each sample tree using an increment borer (Haglöf) at breast height. Transverse sections of 20 μm in thickness were prepared from each core sample using a

Table 1 Local and identified scientific names, stem diameter at 1.3 m above the ground, tree height, and stress-wave velocity of *Artocarpus* sample trees

No.	Local name	Species	D (cm)	TH (m)	SWV (km s^{-1})
1	Dadak	*A. dadah* (AD)	13.3	13.7	3.65
2		*A. nitidus* (AN)	19.9	20.0	4.03
3			18.9	14.5	2.40
4	Kapuak	*A. elasticus* (AE)	26.8	16.0	3.08
5		*A. tamaran* (AT)	20.0	11.4	2.54
6			22.2	13.0	2.76
7	Mentawa	*A. anisophyllus* (AA)	22.8	23.3	3.01
8			25.2	24.2	2.96
9	Pihing	*A. odoratissimus* (AO)	23.3	15.7	3.57
10			23.0	16.7	3.31
11			26.0	14.9	3.66
12			23.5	18.0	3.66
Mean			22.1	16.8	3.22
Standard deviation			3.7	4.0	0.51

D stem diameter at 1.3 m above the ground, *TH* tree height, *SWV* stress-wave velocity

sliding microtome (ROM-380, Yamato Kohki). These sections were stained with safranin, dehydrated with graded ethanol, cleared with xylene, and then mounted in Bioleit. Transverse sectional images were captured using a digital camera (E-P3, Olympus) equipped to a microscope (BX51, Olympus), transferred to a personal computer, and then analyzed to determine the vessel diameter, fiber diameter, and fiber wall thickness using an image analysis software (ImageJ, National Institute of Health). For the measurements, 30 vessels and 50 fibers were used at each radial position.

Small wooden sticks (1 × 1 × 5 mm) were prepared from each core sample for measuring the vessel element length and fiber length. The sticks were macerated in Schulze's solution (6 g potassium chlorate in 100 mL 35% nitric acid). 30 vessel elements and 50 fibers at each radial position were measured using a microprojector (V12, Nikon) and a digital caliper (CD-30C, Mitutoyo).

Basic density and compressive strength

Core samples were cut into small segments at 1 cm intervals from pith to bark and then tested to determine the radial variation of basic density. The green volume of each specimen was measured by the water displacement method, and then the specimens were oven-dried at 105 °C. After reaching a constant weight at 105 °C, the oven-dried weight was measured for each specimen. Basic density was calculated by dividing the oven-dried weight by the green volume.

The other core samples were used for determining the compressive strength parallel to the grain. The core samples were cut into small segments at 5 mm intervals from pith to bark. The values of compressive strength in each specimen were measured using a core sample testing machine (Fractometer II, IML) according to the method described by Matsumoto et al. (2010). The specimens were clamped in the testing machine, and then the load was slowly applied in the longitudinal direction of the specimen. The values of the compressive strength in each specimen were recorded as indicated by the testing machine.

Results and discussion

Growth characteristics and stress-wave velocity

The stem diameter, tree height, and stress-wave velocity of six *Artocarpus* species were listed in Table 1. The stem diameter, tree height, and stress-wave velocity ranged from 13.3 cm in *A. dadah* to 26.8 cm in *A. elasticus*, from 11.4 m in *A. tamaran* to 24.2 m in *A. anisophyllus*, and from 2.40 to 4.03 km s^{-1} in *A. nitidus*, respectively. The mean values of stem diameter, tree height and stress-wave velocity were 22.1 cm, 16.8 m and 3.22 km s^{-1}, respectively, for the 12 trees from the six *Artocarpus* species.

The stress-wave velocity of the stem has been measured in some tropical commercial plantation species (Ishiguri et al. 2007, 2013; Makino et al. 2012; Hidayati et al. 2013). For example, Ishiguri et al. (2007) reported that the stress-wave velocity of 13-year-old *Falcataria moluccana* trees was 3.08 km s^{-1}. In other species, the values of stress-wave velocity were 3.52–3.57 km s^{-1} in 12-year-old *Tectona grandis* trees (Hidayati et al. 2013), 3.59 and 3.75 km s^{-1} in 5- and 7-year-old *Acacia mangium* trees (Makino et al. 2012), and 3.03–3.88 km s^{-1} in 4-year-old *Eucalyptus camaldulensis* trees (Ishiguri et al. 2013). In the present study, with some exceptions, *A. dadah*, *A. nitidus*, and *A. odoratissimus* showed relatively higher stress-wave velocity values compared to those in other tropical commercial plantation species. These results indicate that the Young's modulus of the woods of these three *Artocarpus* species are almost the same or relatively higher compared to that in other commercial plantation species.

Anatomical characteristics

The statistical values of the anatomical characteristics are shown in Tables 2 and 3. The mean values of vessel diameter and vessel element length in each individual ranged from 109 (*A. anisophyllus*) to 204 (*A. tamaran*) µm and 0.34 (*A. dadah*) to 0.48 (*A. elasticus*) mm, respectively. The mean values of the 12 trees were 150 µm in vessel diameter and 0.41 mm in vessel element length. In the fiber morphologies, the mean values of the 12 trees were 19.8 µm in fiber diameter, 1.28 µm in fiber wall thickness, and 1.34 mm in fiber length. The highest and lowest values were observed in *A. elasticus* (35.0 µm) and *A. anisophyllus* (15.5 µm) for fiber diameter, *A. anisophyllus* (1.52 µm) and *A. tamaran* (1.00 µm) for fiber wall thickness, and *A. odoratissimus* (1.51 mm) and *A. nitidus* (1.12 mm) for fiber length.

In *Artocarpus* species, Ogata et al. (2008) reported that the values of vessel diameter, fiber diameter, and fiber length ranged from 180 to 410 µm, 25–45 µm, and 1.2–2.6 mm, respectively. Istikowati et al. (2014) also reported that the mean values of anatomical characteristics in *A. elasticus* were 167 µm in vessel diameter, 0.42 mm in vessel element length, 24.5 µm in fiber diameter, 1.60 µm in fiber wall thickness, and 1.55 mm in fiber length. Each value in this study was slightly lower or almost the same as that reported by Ogata et al. (2008).

In other tropical commercial plantation species, vessel diameter values were reported as 234 µm in *F. moluccana* (Ishiguri et al. 2009), 188 µm in *T. grandis* (Hidayati et al. 2014), and 85–155 µm in *A. mangium* (Nugroho et al. 2012). Vessel element length values were 0.28 mm in *T. grandis* (Hidayati et al. 2014), 0.23–0.25 mm in *Acacia* hybrid (Kim et al. 2008), 0.2 mm in *A. mangium* (Honjo et al. 2005), and 0.24 mm in *Acacia auriculiformis* (Chowdhury et al.

Table 2 Statistical values of vessel morphologies of *Artocarpus* woods

No.	Species	n_1	VD (µm)				VEL (mm)			
			Mean	SD	Min	Max	Mean	SD	Min	Max
1	AD	6	122	20	90	149	0.34	0.02	0.31	0.36
2	AN	9	122	30	74	157	0.36	0.03	0.31	0.39
3		6	110	25	73	140	0.35	0.01	0.34	0.37
4	AE	9	190	24	159	220	0.48	0.03	0.45	0.52
5	AT	9	204	27	150	230	0.40	0.02	0.37	0.43
6		11	160	10	144	179	0.45	0.04	0.38	0.49
7	AA	9	109	20	93	146	0.43	0.03	0.38	0.47
8		12	159	28	116	205	0.41	0.01	0.39	0.43
9	AO	10	158	21	126	195	0.44	0.03	0.40	0.48
10		10	148	14	120	175	0.41	0.02	0.38	0.43
11		13	181	27	133	216	0.42	0.02	0.39	0.45
12		11	130	14	98	140	0.41	0.02	0.39	0.44
Mean/total (n_2 = 12)			150	32	109	204	0.41	0.04	0.34	0.46

n_1 number of radial positions of a sample tree, n_2 number of sample trees, *SD* standard deviation, *Min* minimum, *Max* maximum, *VD* vessel diameter, *VEL* vessel element length

Table 3 Statistical values of fiber morphologies of *Artocarpus* woods

No.	Species	n_1	FD (μm)				FWT (μm)				FL (mm)			
			Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
1	AD	6	15.7	0.7	14.5	16.4	1.46	0.02	1.42	1.49	1.21	0.19	0.90	1.38
2	AN	9	16.2	1.0	14.7	17.7	1.49	0.05	1.41	1.55	1.28	0.13	1.06	1.46
3		6	17.3	0.6	16.7	18.2	1.49	0.03	1.44	1.53	1.12	0.16	0.96	1.36
4	AE	9	35.0	5.9	28.3	43.4	1.10	0.03	1.06	1.16	1.14	0.17	0.96	1.39
5	AT	9	26.3	2.4	22.8	29.1	1.08	0.03	1.05	1.13	1.43	0.24	0.96	1.71
6		11	27.9	3.6	24.0	34.3	1.00	0.03	0.97	1.05	1.35	0.23	0.91	1.57
7	AA	9	15.5	1.0	14.2	17.4	1.45	0.15	1.27	1.67	1.37	0.14	1.14	1.53
8		12	16.0	1.0	14.0	17.2	1.52	0.10	1.35	1.69	1.43	0.14	1.14	1.60
9	AO	10	17.8	0.9	16.2	18.8	1.15	0.03	1.11	1.19	1.50	0.17	1.19	1.69
10		10	16.9	0.7	15.6	18.1	1.11	0.05	1.06	1.20	1.41	0.18	1.07	1.60
11		13	16.3	1.1	15.2	19.2	1.26	0.12	1.08	1.45	1.51	0.17	1.17	1.74
12		11	16.2	0.6	15.4	17.7	1.23	0.07	1.05	1.32	1.37	0.16	1.02	1.54
Mean/total (n_2 = 12)			19.8	6.4	15.5	35.0	1.28	0.19	1.00	1.52	1.34	0.13	1.12	1.51

n_1 number of radial positions of a sample tree, n_2 number of sample trees, *SD* standard deviation, *Min* minimum, *Max* maximum, *FD* fiber diameter, *FWT* fiber wall thickness, *FL* fiber length

2009). Fiber diameter values were 18.2 μm in *F. moluccana* (Ishiguri et al. 2009); 23.4 μm in *T. grandis* (Hidayati et al. 2014); and 18.8 μm in *Acacia* hybrid, 19.4 μm in *A. mangium*, and 16.7 μm in *A. auriculiformis* (Yahya et al. 2010). Fiber wall thickness values were 1.03 μm in *F. moluccana* (Ishiguri et al. 2009); 2.78 μm in *T. grandis* (Hidayati et al. 2014); and 2.51 μm in *Acacia* hybrid, 2.55 μm in *A. mangium*, and 2.81 μm in *A. auriculiformis* (Yahya et al. 2010). Fiber length values were 0.91 mm to 1.17 mm in *F. moluccana* (Ishiguri et al. 2009); 1.38 mm to 1.48 mm in *T. grandis* (Hidayati et al. 2014); 0.86 mm to 0.93 mm in *Acacia* hybrid (Kim et al. 2008); 0.89 mm to 0.94 mm in *A. mangium* (Nugroho et al. 2012); and 0.89 mm to 1.06 mm in *A. auriculiformis* (Chowdhury et al. 2009). For the vessel morphologies of the *Artocarpus* species in this study, the mean values of vessel element length were higher than those of other species. The mean values of vessel diameter for *A. dadah, A. nitidus*, *A. anisophyllus*, and *A. odoratissimus* were within the range of *A. mangium* (Nugroho et al. 2012), and those of *A. elasticus* and *A. tamaran* were close to that of *T. grandis* (Hidayati et al. 2014). Regarding fiber morphologies, the fiber diameter values in *A. elasticus* and *A. tamaran* were larger than those of other common species (Kim et al. 2008; Ishiguri et al. 2009; Yahya et al. 2010; Nugroho et al. 2012; Hidayati et al. 2014). Fiber diameter values in other *Artocarpus* species were similar or smaller than that of *A. auriculiformis* (Yahya et al. 2010). All *Artocarpus* species had a thinner fiber wall thickness than *T. grandis* and *Acacia* species, and had a longer fiber length than *Acacia* species. The fiber wall thickness of *A. tamaran* was similar to that of *F. moluccana* (Ishiguri et al. 2009). The fiber length of *A. tamaran*, *A. anisophyllus*, and *A. odoratissimus* were almost the same as that of *T. grandis* (Hidayati et al. 2014).

Basic density and compressive strength

Radial variation of basic density was shown in Fig. 1. Radial variation petterns were different among species. In *A. dadah* and *A. odoratissimus*, basic density gradually increased from pith to bark and then it showed almost constant value. Almost constant values from pith to bark were found in *A. anisophyllus*. In *A. elasticus* and *A. tamaran*, basic density around pith showed lower values and then it rapidly increased toward the bark. On the other hand, basic density in *A. nitidus* fluctuated from pith to bark. Table 4 shows the mean values of basic density and compressive strength

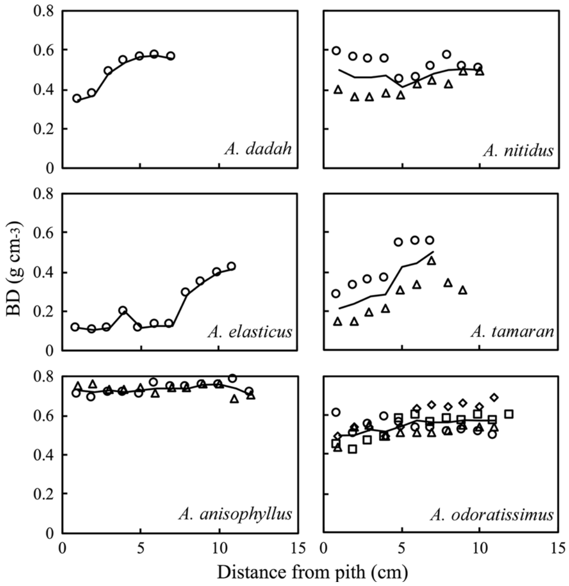

Fig. 1 Radial variation of basic density in six *Artocarpus* species. *Note BD* basic density; circles, triangles, squares, and diamonds in each figure indicate each individual tree. Solid lines indicate mean value in each species

parallel to grain. The mean values of basic density ranged from 0.21 g cm^{-3} in *A. elasticus* to 0.74 g cm^{-3} in *A. anisophyllus*. The mean value for the 12 trees was 0.50 g cm^{-3}. The values of basic density in *Artocarpus* species have been previously reported to be 0.30–0.78 g cm^{-3} in *Artocarpus* sp. (Ogata et al. 2008); 0.50 g cm^{-3} in *A. anisophyllus*, 0.44 g cm^{-3} in *A. dadah*, 0.30 g cm^{-3} in *A. elasticus*, and 0.48 g cm^{-3} in *A. nitidus* (Suzuki 1999); 0.44 g cm^{-3} in *A. chaplasha*, 0.46 g cm^{-3} in *A. heterophyllus*, and 0.45 g cm^{-3} in *A. lakoocha* (Chowdhury et al. 2013); and 0.34 g cm^{-3} in *A. elasticus* (Istikowati et al. 2014). The mean values of basic density in *Artocarpus* species in the present study were within the range of those in the previous studies.

As shown in Table 4, the mean values of compressive strength parallel to grain at green condition ranged from 12.1 MPa in *A. elasticus* to 47.2 MPa in *A. anisophyllus*. In addition, the mean value of the 12 trees was 31.2 MPa. In *A. heterophyllus,* Ruwanpathirana (2014) reported that the compressive strength at 12% moisture content was 39 MPa. Istikowati et al. (2014) reported that the compressive strength at air-dry condition in *A. elasticus* was 37.9 MPa. Considering the difference in the moisture content of the specimens, it is considered that the values of compressive strength in this study were almost the same as those of previous studies.

In other tropical commercial plantation species, the values of basic density were 0.32 g cm^{-3} in *F. moluccana* (Ishiguri et al. 2007), 0.51 g cm^{-3} in *T. grandis* (Hidayati et al. 2014), 0.61–0.69 g cm^{-3} in *Acacia* hybrid (Kim et al. 2008), 0.42 and 0.45 g cm^{-3} in *A. mangium* (Makino et al. 2012), and 0.57 g cm^{-3} in *A. auriculiformis* (Chowdhury et al. 2009). In addition, the values of compressive strength were 37.5 MPa (at green condition) in *T. grandis* (Hidayati

Table 4 Statistical values of basic density and compressive strength parallel to the grain of *Artocarpus* woods

No.	Species	BD (g cm^{-3})					CS (MPa)				
		n_1	Mean	SD	Min	Max	n_1	Mean	SD	Min	Max
1	AD	7	0.49	0.10	0.35	0.57	14	31.9	8.0	20.0	43.0
2	AN	10	0.53	0.05	0.45	0.58	19	30.9	3.4	26.0	38.0
3		10	0.42	0.05	0.37	0.50	17	20.6	2.3	16.0	24.0
4	AE	11	0.21	0.12	0.11	0.42	20	12.1	9.9	4.0	30.0
5	AT	7	0.42	0.12	0.28	0.56	12	19.8	3.2	16.0	26.0
6		9	0.27	0.10	0.15	0.46	16	14.4	7.2	4.0	28.0
7	AA	12	0.73	0.03	0.69	0.78	20	47.2	3.4	42.0	55.0
8		12	0.74	0.02	0.69	0.76	21	43.4	4.3	32.0	50.0
9	AO	11	0.54	0.04	0.49	0.61	22	36.3	4.5	26.0	45.0
10		11	0.52	0.03	0.44	0.55	20	36.2	2.9	32.0	42.0
11		12	0.54	0.07	0.42	0.60	23	41.9	5.3	33.0	57.0
12		11	0.59	0.07	0.49	0.69	20	40.1	4.3	35.0	50.0
Mean/total (n_2 = 12)			0.50	0.16	0.21	0.74		31.2	11.8	12.1	47.2

n_1 number of radial positions of a sample tree (BD and CS were measured at 1 cm and 5 mm intervals from the pith, respectively), *n_2* number of sample trees, *SD* standard deviation, *Min* minimum, *Max* maximum, *BD* basic density, *CS* compressive strength parallel to grain

et al. 2014) and 30.0 and 32.8 MPa (at green condition) in 5- and 7-year-old *A. mangium* trees (Makino et al. 2012). From the obtained results, it is considered that, with a few exceptions, the mean values of basic density and compressive strength in the six *Artocarpus* species studied have almost the same basic density of *Tectona* and *Acacia* species.

Relationships between stress-wave velocity and other properties

There were no significant correlations between the stem diameter or tree height and stress-wave velocity (Fig. 2). It has been reported that no significant correlations were found between the stem diameter and stress-wave velocity in several tropical species (Dickson et al. 2003; Makino et al. 2012; Hidayati et al. 2013); our results are consistent with these. Therefore, it is considered that, in *Artocarpus* species found in secondary forests, fast-growing characteristics do not always relate to the decrease in the strength properties of wood, especially in regards to Young's modulus. On the other hand, no significant correlations were found between stress-wave velocity and other properties (Fig. 1). Therefore, further research is needed for clarifying the properties which are related to stress-wave velocity of stem in *Artocarpus* species.

Relationships between basic density and other properties

The correlation coefficients between basic density and other properties are summarized in Table 5. It is well-known that basic density is one of the indices to predict strength properties in wood (Panshin and de Zeeuw 1980). In the present study, a highly positive correlation coefficient ($r = 0.897$) was obtained between basic density and compressive strength parallel to grain, suggesting that the mechanical properties of *Artocarpus* species can be predicted by measuring the basic density. On the other hand, basic density itself is affected by cell size and the thickness of the cell wall (Panshin and de Zeeuw 1980). Significant correlations were also found between basic density and fiber diameter ($r = -0.831$) or fiber wall thickness ($r = 0.610$). The correlations in the six *Artocarpus* species tested in the present study showed the same tendencies as those in another fast-growing species reported by Ishiguri et al. (2009); in 13-year-old *F. moluccana*, there were significant correlations between basic density and fiber diameter (r = -0.64) or fiber wall thickness ($r = 0.87$).

Utilization of wood from *Artocarpus* species

In the present study, the anatomical characteristics and wood properties were investigated for six *Artocarpus*

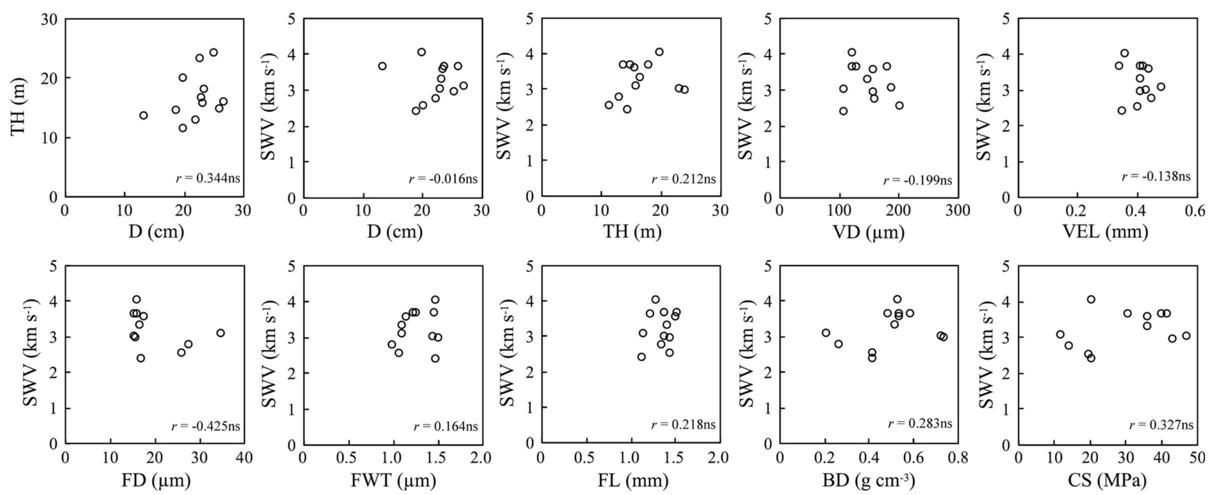

Fig. 2 Relationships between stress-wave velocity and other properties in six *Artocarpus* species. *Note D* stem diameter at 1.3 m above ground, *TH* tree height, *SWV* stress-wave velocity, *VD* vessel diameter, *VEL* vessel element length, *FD* fiber diameter, *FWT* fiber wall thickness, *FL* fiber length, *BD* basic density, *CS* compressive strength parallel to grain, *r* correlation coefficient, *ns* no significance

Table 5 Correlation coefficients between basic density and other characteristics of *Artocarpus* species

Property	Correlation coefficient	
VD	− 0.423	ns
VEL	− 0.257	ns
FD	− 0.831	**
FWT	0.610	*
FL	0.494	ns
CS	0.897	**

SWV stress-wave velocity, *VD* vessel diameter, *VEL* vessel element length, *FD* fiber diameter, *FWT* fiber wall thickness, *FL* fiber length, *CS* compressive strength parallel to grain, *ns* no significance

*Significant at 5% level; **significant at 1% level

species naturally grown in secondary forests in Central Kalimantan, Indonesia. Based on the results, the six *Artocarpus* species have similar or higher strength properties compared to tropical commercial plantation species. It is considered, therefore, that the six *Artocarpus* species used in the present study could produce solid lumber for construction, furniture, and other uses. Although further research is still needed for clarifying the drying and other processing characteristics, the results of the present study suggest that *Artocarpus* species tested here might be suitable tree species for agroforestry in Asian countries to produce wood as solid lumber.

Conclusion

To utilize the wood from unutilized fast-growing tree species in secondary forests, the anatomical characteristics and wood properties were investigated for six *Artocarpus* species naturally regenerated in secondary forests in Central Kalimantan, Indonesia. The mean values of 12 trees from six *Artocarpus* species were 22.1 cm for stem diameter, 16.8 m for tree height, and 3.22 km s^{-1} for stress-wave velocity. Among the six species, *A. dadah*, *A. nitidus*, and *A. odoratissimus* showed relatively higher stress-wave velocity values compared to those in other tropical commercial plantation species. In addition, there were no significant correlations between the stem diameter or tree height and the stress-wave velocity, suggesting that, in *Artocarpus* species, fast-growing characteristics are not always related to the decrease in the Young's modulus of the wood. The mean values of the 12 trees were 150 μm for vessel diameter, 0.41 mm for vessel element length, 19.8 μm for fiber diameter, 1.28 μm for fiber wall thickness, and 1.34 mm for fiber length. In addition, the mean values for basic density and compressive strength parallel to grain in the green condition were 0.50 g cm^{-3} and 31.2 MPa, respectively. A highly positive correlation coefficient ($r = 0.897$) was obtained between basic density and compressive strength, suggesting that the mechanical properties of *Artocarpus* species can be predicted by measuring the basic density. Although other characteristics (e.g., drying and processing characteristics) are not clarified in the present study, it is considered that the six *Artocarpus* species used in the present study could produce solid lumber for construction, furniture, and other uses, suggesting that these species might be alternative tree species for lumber production in agroforestry in Asian countries.

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