Anatomical, Chemical, and Mechanical Properties of Fibrovascular Bundles of *Salacca* (Snake Fruit) Frond

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This research presents the anatomical, chemical, and mechanical properties of fibro-vascular bundles (FVBs) from two species of *Salacca* (snake fruit) frond: *Salaccca sumatrana* Becc. and *Salacca zalacca* Gaert (Voss). The anatomical properties were observed in the cross-section by light microscopy and digital microscopy. The anatomical observation focused on the location of the inner and outer vascular system. In the chemical analysis, FVBs were characterized for cellulose, hemicellulose, Klason lignin, and extractive content. Tensile strength and Young's modulus were investigated, and the structural implications were considered. The FVBs from salacca frond contained vascular tissue in the cross section had new and different vascular type. Generally, the vascular tissue has a wider area than the sclerenchyma tissue. The FVBs of *S. sumatrana* and *S. zalacca* contained 41.75 and 44.60 wt% cellulose, 31.36 and 36.39 wt% hemicellulose, and 27.90 and 33.00 wt% lignin, respectively. The hot water solubility and ethanol-toluene solubility of FVBs of *S. sumatrana* and *S. zalacca* showed that extractive content were 2.96 wt% and 5.55 wt%; 18.54 wt% and 25.00 wt.%, respectively. As the diameter of FVBs increased, the tensile strength and Young's modulus decreased. Increased FVB density will directly increase tensile strength and Young's modulus. Based on the result, it was concluded that the FVBs of salacca type had significantly different properties compared to other palms' FVBs, and this study confirmed the correlation between the physical and mechanical properties of the FVBs from salacca frond.

Keywords: Salacca (snake fruit); Fibrovascular bundles; Tensile strength; Type of vascular tissue

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INTRODUCTION

Indonesia has many options for development of the forest community, such as the intensive agroforestry system between the main plant (tree) and the supporting plant (multi purposes tree species). One of the agroforestry systems, which was developed in Indonesia, is the salacca-based agroforestry system. Salacca belongs to family Palmae or Arecaceae, and is a native plant from the Indonesian-Malaysian region (Mogea 1986; Dransfield *et al.* 2005; Supapvanich *et al*. 2011; Zumaidar *et al*. 2014). The salacca fruits are known as salak (snake fruits). In Indonesia, the two popular snake fruit plants cultivated as a supporting plant are salak Sidempuan (*Salacca sumatrana* Becc.) and salak Pondoh (*Salacca zalacca* Gaert. (Voss). Both plants are cultivated based on the agroforestry system from Java Island and Sumatera Island. Generally, snake fruits are edible with a sweet taste, but the fronds of the salacca tree are not used optimally. Some previous studies showed that salacca fronds have been used as raw material for particleboard with citric acid-based adhesive (Widyorini *et al.* 2018; Widyorini *et al.* 2019) and as the wear component of natural fiber reinforced phenolic (Rohardjo and Ridlo 2019). To optimize utilization as a raw material, however, it is necessary to know the basic properties of the salacca tree fronds. The basic properties of the salacca tree frond from the two species (*S. sumatrana* and *S. zalacca*) have not been reported.

The anatomy of 18 species of palm frond has been described by Zhai *et al.* (2013), and there are many studies on their fibro-vascular bundles structures, including those of coconut trees (Satyanarayana *et al.* 1982), windmill palm (*Trachycarpus fortune*) (Zhai *et al.* 2012), non-wood plant fiber bundles (Munawar *et al.* 2007), and Nypa palm (*Nypa fruticans*) (Tamunaidu and Saka 2011). Natural fibers are being developed as a raw material to substitute for wood in natural fiber composites. Natural fiber can replace synthetic fiber as a raw material for a cheaper, renewable, and sustainable alternative (Pickering *et al.* 2016). Munawar *et al.* (2007) characterized the morphology, physical, and mechanical properties of seven natural fibers of non-wood that could be used as a raw material of the composite board. There has been research on the structure of monocot anatomy, especially the fiber bundles, vascular bundles, or fibro-vascular bundles. Grosser and Liese (1971) observed bamboo anatomical structures throughout Asia by emphasizing the differences in the structure of vascular bundles.

In addition, Baley (2002) conducted research on the characteristics of the natural fiber of flax as a raw material of the composite board. Flax contains fiber bundles composed of between 10 to 40 fibers bound by lignin and pectin. The tensile strength of flax is approximately 600 to 2000 MPa, which is sufficient as a raw material of the composite board. Furthermore, fiber strands from oil palm empty fruit bunches are similar in structure to those of the leaf-sheath coconut tree (Law *et al.* 2007).

This study investigated the characteristics of the fronds of salacca, especially fibro-vascular bundles (FVBs) as a natural fiber. The palm tree has FVBs with anatomical properties such us long fiber (sclerenchyma fiber), vascular and parenchyma cells in the stem, leaf sheath in the fruit. The FVB tissue structure depends on the palm species (Zhai *et al.* 2013). Zhai *et al.* (2013) characterized 18 leaf-sheath FVBs of palm. The FVBs can be included as part of the natural fiber. Darmanto *et al.* (2017a,b) separated the salacca frond into fiber and reported that the fiber had a tensile strength of 160 MPa. Furthermore, after alkali, alkali-steaming, and alkali-steam explosion treatment, the fiber can improve in strength to 275 MPa, 220 MPa, and 226 MPa, respectively. Isolation of cellulose from salacca frond fibers by alkali treatment and bleaching with hydrogen peroxide successfully increased α-cellulose content, decreased of lignin content, and increased percentage of index crystallinity (Yudha *et al.* 2018). Unfortunately, the properties of salacca frond and their relationship with the mechanical properties of FVBs have not been reported. This paper presents the anatomical characteristics, physical properties, mechanical properties, and chemical properties of FVBs from two species of salacca (*S. sumatrana* and *S. zalacca*), which were cultivated from the agroforestry system in Indonesia.

EXPERIMENTAL

Materials

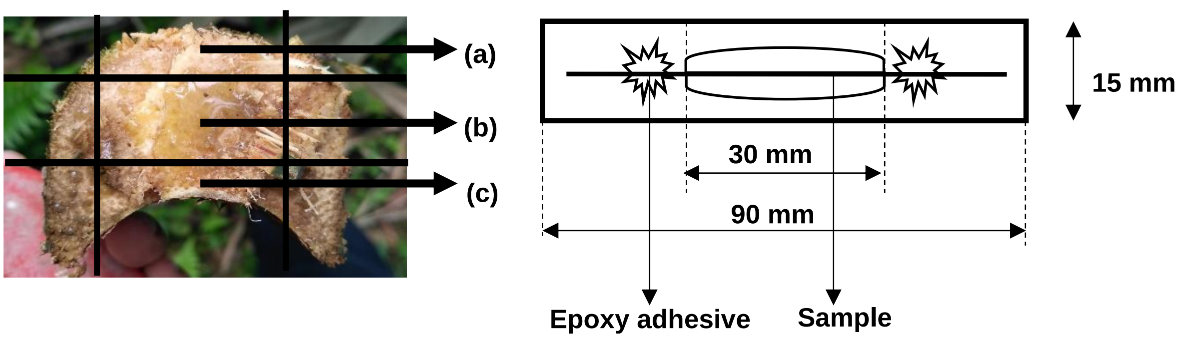
The salacca fronds were collected from two different growth locations of the agroforestry system in Indonesia. They were salak sidempuan (*S. sumatrana*) from

Tapanuli Selatan (Province of Sumatera Utara), and salak pondoh (*S. zalacca*) from Sleman (Province of Yogyakarta). Sumatera Utara Province is located north of the equator, while Yogyakarta province is located south of the equator. The FVBs were obtained from the fronds of 15- to 25-year-old salacca trees. The fronds were hand-picked from the plant at the height of 5 cm from the main stem. Before being soaked in water, the leaf was removed from the main frond and was rinsed in cold water (23 °C) to remove soil and mud. The FVBs were collected after soaking in water for 4 weeks. The FVBs were air-dried to remove excess water and moisture prior to use in further experiments.

Methods

Sample preparation

The specimen preparation for anatomical observation of salacca fronds in this study was based on the methods of Jansen *et al.* (1998). No more than two fronds of each salacca species were cut approximately 1 to 2 cm^2 on three positions of the transverse section. The three positions were observed based on the concept of the inner and outer vascular system developed by Zimmermann and Tomlinson (1972). The inner vascular system is that of the central transverse section, and the outer vascular system is that of the peripheral near cortex. In this research, the outer vascular system was divided into two parts, namely the convex vascular system part and concave vascular system part (Fig. 1A). Cross-section (transversal) orientations were prioritized as the focus of observations. To soften the specimens, the block specimens of the frond were immersed in a boiling water mixture of glycerin and water (1:10 volume ratio) for 2 h until the specimen became supersaturated. Transverse sections of the block specimens (10 to 15 µm thick) were cut using a sliding microtome with a metal knife. The samples were stained with safranin to highlight the area of fibro-vascular bundles.



A B

Fig. 1. A. Pattern of transverse section for anatomical observation: (a) convex vascular system; (b) inner vascular system, and (c) concave vascular system. B: Mounting of FVB on the paper frame for mechanical testing

Observation of anatomical properties

The anatomical properties of FVB included measurement of the number of FVBs per 4 mm^2 on the transverse section area, total transverse area of FVB, vascular tissue area, fiber tissue area, the ratio of vascular area to the total area, the ratio of non-vascular tissue area to the total transverse area, and the ratio vascular tissue area to the non-vascular tissue area. These parameters were measured to know relationship between anatomical and physical properties. The anatomical characteristics were observed with a light microscope

(Olympus BX 51, Tokyo, Japan) equipped with a digital camera (Olympus DP 70, Tokyo, Japan) and imaging analysis software system (ImageJ; v.1.46r). The cell types, fibers, and vascular tissue localization were observed. Additionally, the number of sclerenchyma fibers and vascular tissue occupying the area of transverse sections were observed. Based on the Zhai *et al.* (2013) methods, the number of FVBs per 4 mm^2 was calculated on the transverse section. In this research, the number of FVBs per 4 mm^2 was calculated on three positions of transverse sectional (the convex vascular system, concave vascular system, and inner vascular system). The ratio of vascular tissue area or sclerenchyma fiber to the total transverse sectional area of FVBs was calculated.

Physical and mechanical properties measurement

The FVBs were air-dried (moisture content: 8 to 12 wt%), and 100 replicates were measured. The specimen size was approximately 90 mm in length. The FVBs were fixed on paper frames with a 30 mm gauge length by medium-viscosity epoxy adhesives (ALF Epoxy adhesive, P.T Alfaglos, Semarang, Indonesia) according to the ASTM D-3379-75 (1989). Previously, the diameter of each FVBs was measured using a handheld digital microscope (dino-lite edge 3.0 AM73915MZTL, New Taipei City, Taiwan) and analyzed using dino-lite software V.2.0 at 100 samples of FVBs. The specimens were conditioned at 60% relative humidity and 20°C for a week before mechanical testing. The mechanical properties of FVBs were determined using a universal testing machine (Tensilon RTF 1350, Tokyo, Japan) with a crosshead speed of 1 mm/min. Prior to testing, the middle part of the supporting paper was cut (Fig. 1B).

Chemical content analysis

According to ASTM D 1110-84 (2013), extractives were removed from the oven-dried samples (2 g) by extraction with boiling water for 3 h. The weight loss from this step was defined as hot water extractive solubility. The ASTM D 1105-96 (2013) was used to prepare extractive-free samples. An ethanol-toluene mixture (ratio 1 L:427 mL) was used to remove the extractive of oven dried samples (2 g) by the Soxhlet extraction method for 4 h. For the extractive-free samples, the cellulose (ASTM D 1103-84 2013), hemicellulose (ASTM D 1104-84 2013), and lignin Klason (ASTM D 1106-84 2013) composition was determined. All analyses were conducted in triplicate.

RESULT AND DISCUSSION

Anatomical Properties

Fibrovascular bundles of S. sumatrana

The microscopic characteristic of frond shows the organization of the inner and outer of vascular system of *S. sumatrana*, as shown in Fig. 2A. The FVBs were different in position on the cross section; they were not uniform in size and shape. Zhai *et al.* (2013) divided FVBs into three types based on differences in diameter and location within a single frond. Type A is a rounded vascular tissue located in the central region of the FVB; type B is rounded/angular vascular tissue located in the marginal region of the FVB. Type C is aliform vascular tissue in the region of the fibro-vascular bundles. In the present research, the new types of FVBs were found on a different position of the vascular system. The outer vascular system between the convex and concave vascular system had a different shape of FVBs. Fibro-vascular bundles in the convex vascular system of the frond had a round shape, while those in the concave vascular system had an oval shape. The FVBs in the outer vascular system (peripheral area) of frond had wider sclerenchyma fibers than vascular tissue. The shape of FVBs in the inner vascular system of the frond was oval, but the vascular tissue had a wider area than the sclerenchyma fibers.

Vascular tissue is clear, but lumens are not uniform in size and shape in each position. The vascular tissue of FVB of *S. sumatrana* has several lumens, which consists of a large lumen that is surrounded by a small lumen (Fig. 2A). Generally, the sclerenchyma fibers is around the vascular tissue for each FVB, but the tissue area was different for each transverse sectional of FVBs.

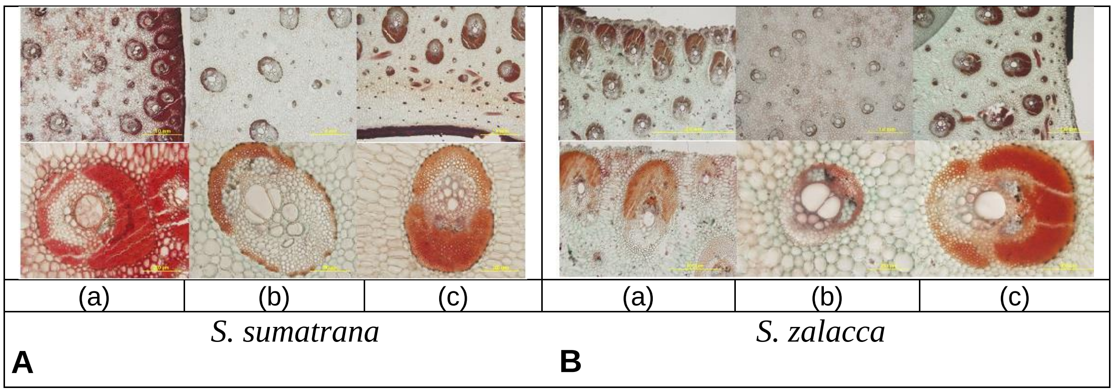


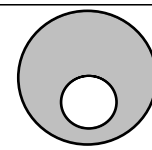
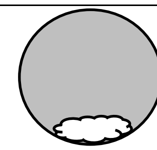
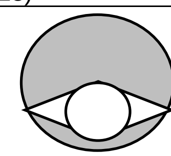
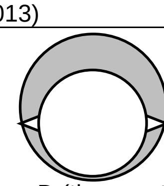
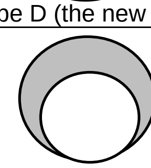
Fig. 2. Transverse sectional image of frond fibro-vascular bundles: A: *S. sumatrana*, B: *S. zalacca*, (a) convex vascular system, (b) inner vascular system, and (c) concave vascular system

Fibrovascular bundles of S. zalacca

The transverse sectional of the FVBs of *S. zalacca* is illustrated in Fig. 2B. According to the classification by Zhai *et al.* (2013), the FVB of *S. zalacca* was almost similar with type C, but the aliform pattern was not clear in the convex and inner vascular system. The vascular tissue of the FVB of *S. salacca* has several lumens, but the lumen was dominated by a wide area. FVBs in the convex vascular system and the inner vascular system of frond had sclerenchyma fibers that did not encircle vascular tissue. Furthermore, the shape of FVB in the convex vascular system was oval. The FVB in the concave vascular system were oval, but the sclerenchyma fibers around the vascular tissue different with the FVB in the convex vascular system. The shape of FVB in the inner vascular system of the frond was round, and the vascular tissue had a wider area compared with the sclerenchyma fibers.

Generally, the salacca vascular tissue had a different type on each position based on wide area of vascular tissue and sclerenchyma fibers. Rüggeberg *et al.* (2009) reported that the vascular bundles of stem of the Mexican fan palm (*Washingtonia robusta)* had a different type between stem periphery and cortical zone. They were classified of the vascular tissue type based on cell wall thickness. The vascular tissue type on inner position of salacca frond had a wider area compared with the sclerenchyma fibers, and types D and E tissues were found. These two types of FVB showed correlation to the phylogenetic classification by Dransfield *et al*. (2005; 2008), as illustrated in Table 1.

Table 1. Type of Vascular Tissue in FVBs of Salacca Compared to FVBs of 14 Genera of palm (Arecaceae) from Zhai *et al.* (2013)

Family	Subfamily	Tribe	Subtribe	Genus	Vascular tissue type
ARECACEAE	ARECOIDEAE	*Cocoseae*	*Attaleinae*	*Butia*	 Type A (Zhai *et al.* 2013)
				Cocos	
				Syagrus	
			Elaeidinae	*Elaeis*	
	CORYPHOIDEAE	*Borasseae*	*Hyphaeninae*	*Medamia*	
		Phoeniceae	-	*Phoenix*	
		Caryoteae	-	*Arenga*	 Type B (Zhai *et al.*. 2013)
				Coryota	
		Corypheae	-	*Corypha*	 Type C (Zhai *et al.* 2013)
		Sabaleae	-	*Sabal*	
		Trachycarpeae	-	*Washingtoniae*	
			Livistoniae	*Livistona*	
			Rhapidinae	*Trachycarpus*	
				Rhapis	Type A (Zhai *et al.* 2013)
	CALAMOIDEAE	*Calamae*	*Salaccinae*	*Salacca*	 Type D (the new type)
				S. sumatrana	
				S. zalacca	 type E (the new type)

Note: The table shows the phylogenetic classification of genera of palms (Arecaceae), redrawn from Dransfield *et al.* (2005; 2008). The gray area is occupied by sclerenchyma fibers and the white area by a vascular tissue.

Anatomical properties of fibro-vascular bundles

The frequency of FVB in *S. sumatrana* was between 3 to 5 FVB per 4 mm^2 in the convex vascular system 1 to 2 FVB per 4 mm^2 in the concave vascular system, and 0 to 1 FVB per 4 mm^2 in the inner vascular system. Similar to *S. sumatrana*, the frequency of FVBs in *S. zalacca* only differed in the convex vascular system of frond, where values were between 3 to 4 FVB per 4 mm^2.

The total transverse area of FVBs of the *S. sumatrana* and *S. zalacca* was 0.589 ± 0.17 mm^2 and 0.455 ± 0.10 mm^2, respectively. The difference between FVB and natural fibers (fiber bundles) was found in vascular tissue in FVB, but the vascular tissue was not found in natural fibers. Vascular tissue contains vessels that improve porosity properties. Increasing the lumens (like a vessel in the vascular tissue) increases the porosity and decreases the density of the fiber (Baley 2002; Munawar *et al.* 2007). Thus, the presence of non-vascular tissue increases density. In this research, vascular and non-vascular tissue areas were calculated. The vascular tissue area of FVB *S. sumatrana* and *S. zalacca* were 0.059 ± 0.01 mm^2 and 0.054 ± 0.14 mm^2, compared with the non-vascular tissue area at 0.531 ± 0.15 mm^2 and 0.401 ± 0.09 mm^2, respectively. The ratio of vascular tissue to non-vascular tissue of FVB in *S. sumatrana* and *S. zalacca* were 11.25 ± 0.87% and 13.83 ± 3.29%, respectively. Based on these results, the density of the FVB in *S. sumatrana* was higher than in *S. zalacca*. The ratio of vascular tissue and the total area of FVB in *S. sumatrana* was lower than in *S. zalacca*; the ratio of non-vascular compared with the total area of FVB in *S. sumatrana* was higher than in *S. zalacca.*

Table 2. Anatomical Properties of Salacca FVBs

Properties	Species of snake fruit	
	S. sumatrana	*S. zalacca*
Number of fibro-vascular bundles per 4 mm^2		
- Convex vascular system of frond	3-5	3-4
- Inner vascular system of frond	1-2	1-2
- Concave vascular system of frond	0-1	0-1
Total transverse area of FVBs (mm^2)	0.589 ± 0.17	0.455 ± 0.10
Vascular tissue area (mm^2)	0.059 ± 0.01	0.054 ± 0.14
Non-vascular tissue area (mm^2)	0.531 ± 0.15	0.401 ± 0.09
Ratio of vascular tissue area to total transverse area of FVBs (%)	9.92 ± 0.70	12.08 ± 2.40
Ratio of non-vascular tissue area to total transverse area of FVBs (%)	90.07 ± 0.70	87.92 ± 2.40
Ratio vascular tissue area to non-vascular tissue area (%)	11.25 ± 0.87	13.83 ± 3.29

Chemical Properties

Table 3 shows the chemical compositions of FVB of *S. sumatrana* and *S. zalacca*. Chemical analysis of *S. sumatrana* FVB indicated that the main components are α-cellulose (44.6%), hemicellulose (31.4%), and lignin (33.0%). For *S. zalacca*, the main components are α-cellulose (41.8%), hemicellulose (36.4%), and lignin (27.9%). Darmanto *et al.* (2107) reported that the major components of a single fiber in *S. zalacca* are cellulose (47.2%), holocellulose (79.1%), and lignin (22.3%). These results were relatively higher in cellulose and lower in lignin compared to the current study, and the hemicellulose was relatively similar to the results obtained here. Tomimura (1992) reported the lignin content of vascular bundles of oil palm trunk was 15.7%, which is comparable to the present result (33.0% for *S. sumatrana* and 27.9% for *S. zalacca*). However, the main components of oil palm trunk are 73.1% holocellulose, 41.0% α-cellulose, and 24.5% lignin (Khalil *et al.* 2008), and Abe *et al.* (2013) also reported that the main chemistry component of oil palm vascular bundles were α-cellulose (42.5%), hemicellulose (37.6%), and lignin (16.1%). These results were relatively similar to those obtained in this study. The Klason lignin content of fibrovascular bundles from the different 18 species, as determined by Zhai *et al.* (2013), have a mean value of 29.6%, which is relatively higher than fibrovascular bundles of salacca frond. In addition, Fathi *et al.* (2014) observed the topochemical distribution of lignin in vascular bundles by UV-microspectrophotometry (UMSP) and stated that there is a relationship between degree of lignification and the tensile strength properties of vascular bundle of coconut wood. Tensile strength increased with a decreasing of lignification.

Furthermore, the chemistry component that soluble in hot water of *S. sumatrana* and *S. zalacca* were 55% and 2.96%, soluble in ethanol-toluene were 25.00% and 18.54%, and ash content were 0.89% and 1.28%, respectively. Tomimura (1992) reported that the ash content of vascular bundles of oil palm trunk is 2.2% higher than FVB from salacca frond. Abe *at al.* (2013) stated the extractive component of vascular bundles of coconut wood is 2.54 % lower than FVBs from salacca frond.

Table 3. Chemical Properties of Salacca FVBs

Chemical content of FVB	Species of snake fruit	
	S. sumatrana (%wt)	*S. zalacca* (%wt)
Cellulose	44.60	41.75
Hemicellulose	31.36	36.39
Klason Lignin	33.00	27.90
Solubility in Hot water	5.55	2.96
Solubility Ethanol-toluene	25.00	18.54
Solubility Ash content	0.89	1.28

Physical and Mechanical Properties

The physical and mechanical properties of FVBs of salacca frond are shown in Table 4. The average diameter of FVBs in *S. sumatrana* and *S. zalacca* was 0.047 ± 0.14 mm and 0.036 ± 0.01 mm, respectively. The density of FVBs of *S. sumatrana* (0.46 ± 0.15 g/cm^3) was higher than *S. zalacca* (0.35 ± 0.11 g/cm^3). Furthermore, in the natural fiber, such us non wood plant fiber bundles which was described by Munawar *et al.* (2007), the density of fiber bundles decreases with increasing diameter of fiber bundles. Unfortunately, Baley (2002) reported that flax fiber shows a different relationship, whereby the size of lumens of flax fiber increased with the increasing of diameter. Increasing the lumen size will increase the porosity of the fiber and decrease the density of the fiber. In this research, FVBs of salacca has a vascular tissue that make the porosity. Increasing the porosity of the FVBs will decrease the density.

Table 4. Physical and Mechanical Properties of Salacca FVBs

Physical and Mechanical properties of Fibro-vascular Bundles	Species of Snake Fruit	
	S. sumatrana	*S. zalacca*
Diameter (mm)	0.047 ± 0.14	0.036 ± 0.01
Density (g/cm^3)	0.46 ± 0.15	0.35 ± 0.11
Tensile strength (MPa)	212.75 ± 97.78	193.51± 47.39
Young' modulus (GPa)	3.03 ± 0.91	2.25 ± 0.60
Specific tensile strength (MPa)	495.69 ± 236.86	602.30 ± 215.85
Specific young' modulus (GPa)	7.09± 2.5	6.93 ± 2.36

Typical stress-strain (S-S) curves for FVB from two salacca species are illustrated in Fig. 3. The S-S curve between *S. sumatrana* and *S. zalacca* shows breakage at 13.7% and 10.5%, respectively. The breakage strain of single fibro-vascular bundles of salacca showed much higher values than those in non-timber plants, including flax (3.3%), jute (8.2%), seagrass (3.4%), sisal (3 to 7%), abaca/banana (1 to 3.5%), ramie bast fiber, sanseviera leaf fiber, pineapple leaf fiber (2 to 6%) (Satyanarayana *et al.* 1982; Baley 2002; Munawar *et al.* 2007); *Cocos nucifera* L (9%), *Butia capitate* (Mart.) Becc. (11%), *Rhapis excels* (Thunb) A. Henry (11%), *Corypha umbraculifera* L (10%), *Trachycarpus fortune* (Hook) H. Wendl. (12%), and *Sabal umbraculifera* Mart. (13%) (Zhai *et al.* 2013); maize fiber bundles (2.5-3%) (Huang *et al.* 2016); vascular bundles of royal palm

(*Roystonea regia*) (1.5%) (Wang *et al.* 2014); Coconut palm wood (1 to 2%) (Fathi, and Frühwald 2014).

Unfortunately, the breakage values were lower than windmill palm (*Trachycarpus fortunei*) (39.5 to 55.2%) (Zhai *et al.* 2012); Coconut husk fiber (24%) (Munawar *et al.* 2007); *Syagrus romanzoffiana* (Cham.) Glassman (25%), *Elaeis guineensis* Jacq. (17%), *Medemia nobilis* (hildebrant and H. Wendl.) Gall. (24%), *Phoenix dactylifera* L. (25%), *Phoenix roebelenii* O'brien. (21%), *Caryota monostachya* Becc. (40%), *Caryota urens* L. (62%), and *Washingtonia filifera* (Linden ex Andre) H. Wendl. ex de Bary. (21%). (Zhai *et al.* 2013).

The tensile strength FVBs of *S. sumatrana* and *S. salacca* were 212.75 ± 97.78 MPa and 193.51± 47.39 MPa, respectively, and the specific tensile strength were 495.69 ± 236.86 MPa and 602.30 ± 215.85 MPa, respectively (Table 4). The values of the tensile strength were lower than fibrovascular bundles of *Elaeis guineensis* frond (228 MPa) (Zhai *et al.* 2013); natural fiber, including ramie bast (849 MPa), pineapple leaf (654 MPa), kenaf bast (473 MPa), Sanseviera leaf (562 MPa), sisal leaf (375 MPa), and abaca leaf (452 MPa) (Munawar *et al.* 2007); flax (1339 MPa), jute (466 MPa), seagrass (573 MPa), sisal (568–640 MPa) (Satyanarayana *et al.* 1982; Baley 2002; Razera and Frollini 2003; Davies *et al.* 2007). Interestingly, previous research by Darmanto *et al.* (2017a,b), reported that the tensile strength without alkali treatment was lower than values the present research, but these values were successfully increased by alkali treatment, alkali-steam treatment, and alkali-steam explosion treatment (275 MPa, 220 MPa, and 225.75 MPa, respectively). In addition, the tensile strength of FVBs of salacca frond were higher than coconut husk fiber (137 MPa) (Munawar *et al.* 2007) and fibrovascular bundles of 17 genera palm had been investigated by Zhai *et al.* (2013).

The Young's modulus of FVBs of *S. sumatrana* and *S. salacca* were 3.03 ± 0.91 and 2.25 ± 0.60 GPa, respectively and the specific Young's modulus were 7.09± 2.5 and 6.93 ± 2.36 GPa, respectively (Table 4). The Young's modulus of FVBs salacca were lower than those of flax (58 GPa), jute (26.5 GPa), seagrass (19.8 GPa) (Satyanarayana *et al.* 1982; Baley 2002; Davies *et al.* 2007); ramie bast (28.4 Gpa), pineapple leaf (27 GPa), kenaf bast (25.1 GPa), sanseiviera leaf (14.0 GPa), abaca leaf (12.9 GPa), and sisal leaf (9.1 GPa) (Munawar *et al.* 2007). The Young's modulus of *S. sumatrana* were higher than FVBs of 17 genera palm were investigated by Zhai *et al.* (2013), unfortunately, the Young's modulus of *S. salacca* were lower than *Arenga engleri* (2.9 GPa), *Butia capitata* (2.5 GPa) and *Rhapis excelsa* (2.9 GPa) (Zhai *et al.* 2013).

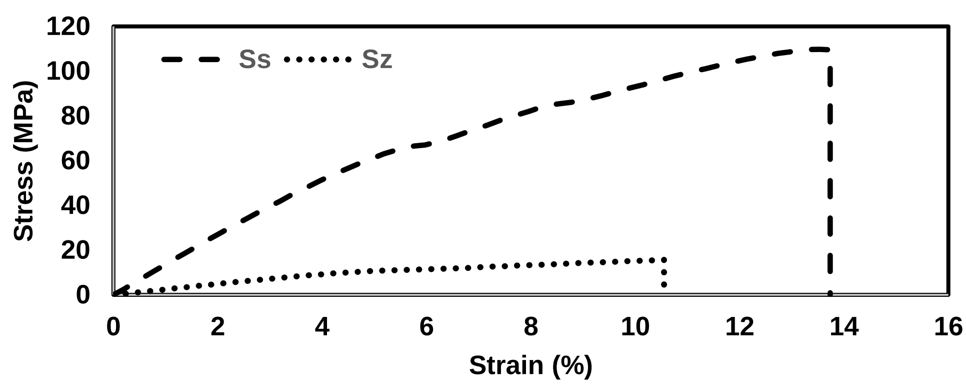


Fig. 3. Typical stress-strain curve of single fibro-vascular bundles of Salacca frond. SS: *S. sumatrana* and Sz: *S. zalacca*

Relationships between Physical and Mechanical Properties

The relationship between physical and mechanical properties from *S. sumatrana* and *S. zalacca* are illustrated in Figs. 4 and 5. The curves show an increasing trend in the diameter of FVB, with decreasing trends in the tensile strength and Young's modulus in two fibro-vascular bundles of frond salacca species. Zhai *et al.* (2013) reported that the tensile strength and Young's modulus showed a decreasing trend with the increase in the diameter of fibrovascular bundles of 18 genera of palm. These conclusions are consistent with phenomenon that have been reported for fiber bundles of flax (Baley 2002), ramie bast, abaca leaf fiber, and pineapple leaf fiber, sansevieria leaf fiber, sisal leaf fiber, coconut husk fiber, and kenaf bast fiber (Munawar *et al.* 2007). Zhai *et al*. (2012) reported that the thick-walled sclerenchyma fibers predominantly contribute to the mechanical properties of fibrovascular bundles in windmill palm, while vessel and phloem tissues tend to reduce mechanical strength.

The relationships between density and mechanical properties showed that the increasing trend of density is directly proportional to the increase in tensile strength and Young's modulus in two fibro-vascular bundles of frond salacca species. Density of the FVBs influenced the ratio of the vascular tissue to the total transverse area of FVBs. The higher of the ratio of the vascular tissue to the transverse area of FVBs will decrease density, and would be a factor that affects mechanical properties. Zhai *et al.* (2012) investigated the tensile strength of windmill palm (*Trachycarpus fortunei*) fiber bundles and its structural implications and reported that the fiber in the fibro-vascular bundles plays a role in increasing mechanical properties, whereas the presence of vessels and phloem tends to reduce mechanical properties.

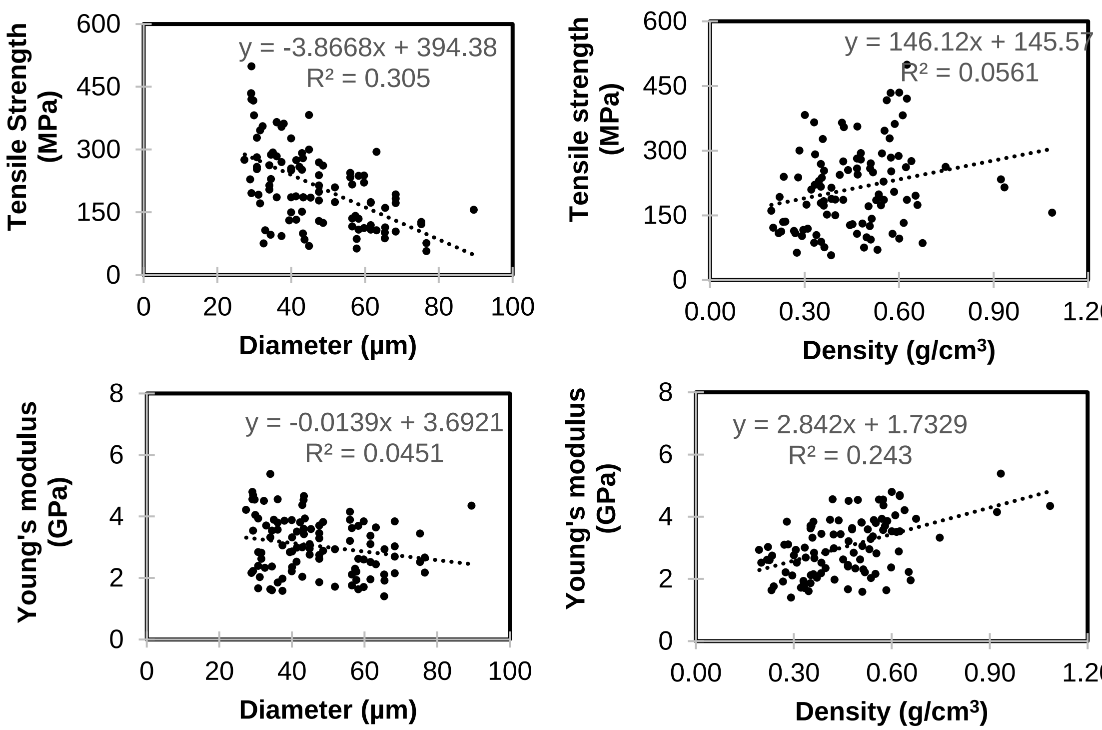


Fig. 4. Relationships between diameter and tensile strength (P< 0.000 **); density and tensile strength (P< 0.017*); diameter and Young's modulus (P< 0.033*); and density and Young's modulus (P< 0.000 **) of single fibro-vascular bundles of *S. sumatrana* frond

The results indicated that the physical properties (density and diameter) and mechanical properties (tensile strength and Young's modulus) of the fibrovascular bundles are closely related to the anatomical characteristics. For the *S. sumatrana*, the relationships between diameter and tensile strength; and between density and Young's modulus is significantly higher. Unfortunately, the relationship between density and tensile strength; between diameter and Young's modulus is significantly lower. For the *S. zalacca*, the relationship between diameter and tensile strength, between density and tensile strength, and between density and Young's modulus is significantly higher, only the relationship between diameter and Young's modulus was found not to be significant. In addition, a low R-squared value indicates that the relationships between tensile strength with density and diameter were weak. There were might other factors which influence relationships between tensile strength with density and diameter. We presume that FVBs porosity contributes to it. Furthermore, the FVBs contain vascular tissues which mostly consist of high porosity vessels.

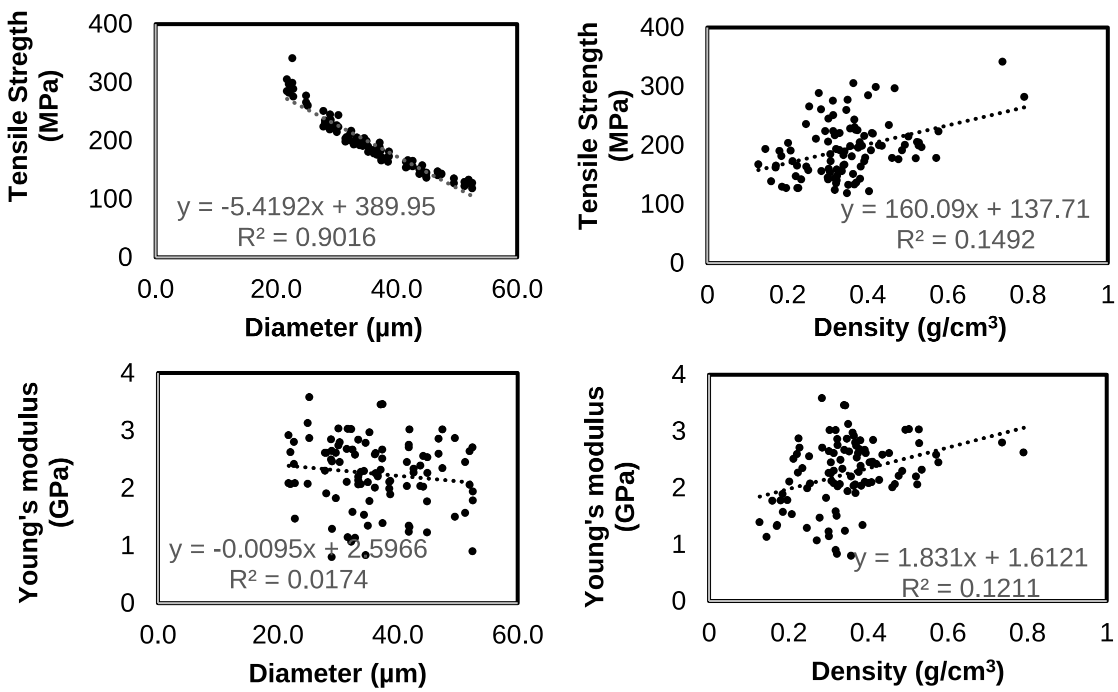


Fig. 5. Relationships between diameter and tensile strength ($P < 0.000^{**}$); density and tensile strength ($P < 0.000^{**}$); diameter and Young's modulus ($P < 0.191^{ns}$); and density and Young's modulus ($P < 0.000^{**}$) of single fibro-vascular bundles of *S. zalacca* frond

Based on the result of physical and mechanical properties, this research concluded that the tensile strength and Young's modulus showed a decreasing tendency with an increase in the diameter of the fibrovascular bundles. But, the increase density of the fibrovascular bundles showed that increasing tendency the tensile strength and Young's modulus. In the future, FVBs can be used as an alternative raw material as a substitute for wood in the manufacture of structural composite boards based on fibrovascular bundles such as oriented composite board.

CONCLUSIONS

1. Salacca frond has a different type of vascular tissue between inner and outer vascular system. In the inner position, the shape of vascular tissue of *S. sumatrana* frond is oval, while shape of vascular tissue of *S. salacca* frond is round. But, for both of them, the vascular tissue had a wider area than the sclerenchyma tissue.
2. In the outer position of *S. sumatrana* frond, both of convex vascular and concave vascular have a different type of vascular tissue. Fibro-vascular bundles (FVBs) in the convex vascular system of the frond have a round shape, while those in the concave vascular system have an oval shape. The FVBs in the outer vascular system (peripheral area) of frond have wider sclerenchyma tissue than vascular tissue.
3. In the outer position of *S. zalacca* frond, the shape of vascular tissue in the convex and concave vascular system is oval, but the sclerenchyma tissue has different shape between the convex and concave vascular system.
4. The major chemical content of FVBs is relatively similar to the previous research about other species of fibrovascular bundles.
5. In this research, relationships were found between the physical (diameter and density) and mechanical (tensile strength and Young's modulus) properties of fibro-vascular bundles of salacca frond.
6. The FVBs is recommended to be an alternative raw material in the manufacture of oriented composite board.

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