

Comparative Study on Chemical Composition, Physical, Tensile, and Thermal Properties of Sugar Palm Fiber (*Arenga pinnata*) Obtained from Different Geographical Locations

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Physical, mechanical, chemical, and thermal properties of sugar palm (*Arenga pinnata*) fiber were investigated for specimens obtained from three different locations: Kuala Jempol (Peninsular Malaysia), Tawau (West Malaysia), and Tasik Malaya (Indonesia). The morphology of the fiber were observed through scanning electron microscopy (SEM), the thermal properties by thermogravimetric analysis (TGA), tensile properties according to ASTM D3379, and chemical analysis by using neutral detergent fiber (NDF) and acid detergent fiber (ADF). This study confirmed that in sugar palm fiber, the highest chemical content of cellulose resulted in the highest strength and thermal stability of the fiber. Fiber originating from Kuala Jempol had the highest cellulose content of 44.53%, followed by Indonesia (44.47%) and Tawau (43.75%). Kuala Jempol fiber (233.28 MPa) also had the highest tensile strength, followed by Indonesia (211.03 MPa) and Tawau (201.30 MPa), which was affected by the cellulose content in the fiber. Thus, fiber originating from Kuala Jempol had better quality than the others as a reinforcement material in manufacturing of polymer composites.

Keywords: Sugar palm fiber; Physical properties; Mechanical properties; Chemical properties; Thermal properties

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INTRODUCTION

The sugar palm tree (*Arenga pinnata*) is a multipurpose tree. In Malaysia, it is found in Negeri Sembilan, Johor, Perak, Pahang, and Sabah. Most parts of this tree are useable for various products. Traditionally, the palm sap is processed to produce enau or sugar palm syrup. In Malaysia, enau is used widely in cooking as a main ingredient for traditional cakes such as dodol, wajik, and pengat. Aside from cooking, sap from sugar palm trees can be used to produce bioethanol through fermentation (Ishak *et al.* 2012; Sanyang *et al.* 2016). The fruit from sugar palm trees can be consumed raw or as an ingredient for desserts.

Sugar palm trees have a straight trunk and can grow to a height of 20 m to 30 m. The trunk can be used for producing furniture or utensils such as ladles and spatulas. The trunk of the sugar palm tree is covered by black fiber known as ijuk. Ijuk is used traditionally to make brooms, ropes, hand crafts, water filters, and fish catchers (Mogea *et al.* 1991). Sugar palm fibre has been found to have great potential as fibre

reinforcement in polymer matrix composites such as the making of boat from dugar palm fiber composites (Misri *et al.* 2010).

Unlike other natural fibers, ijuk has many benefits such as high tensile strength, resistance to decay and high humidity, low cost, and availability. Moreover, ijuk fiber does not need any secondary process and is ready to use (Leman *et al.* 2008). Other natural fibers require secondary processes such as water retting or mechanical decorticating before the fibers are used.

There are many studies on composites using natural materials to replace synthetic and glass fibers, as the use of materials from glass and synthetics can lead to environmental pollution. Natural fibers with outstanding strength comparable to synthetic and glass fibers have attracted the attention of researchers to develop environmentally friendly material from natural fiber composites. Natural fibers are eco-friendly, low in production cost, recyclable, low in density, and nonabrasive (Mishra *et al.* 2001).

A study on sugar palm fiber (SPF) properties from different tree heights (1 m, 3 m, 5 m, 7 m, 9 m, 11 m, 13 m, and 15 m) by Ishak *et al.* (2012) found that properties of sugar palm fiber were influenced by the maturity of the tree. Fiber at the bottom of tree (1 m and 3 m) shows low tensile value because of fiber decay. The fiber at the middle of tree (11 m and 13 m) shows a high tensile value, and fiber at the top of the tree (15 m) shows medium tensile value due to low maturity and young age. Few research studies explore the effect of geographical location or cultivation method on the strength of sugar palm fiber. Thus, it is important to expand the scope of research to determine the factors that improve the quality of sugar palm fiber.

This paper studies the chemical composition and the physical, tensile, and thermal properties of sugar palm fiber obtained from different geographical locations (Kuala Jempol, Tawau, and Indonesia). Results are expected to provide information that is beneficial for the selection of the optimum fiber properties of sugar.

EXPERIMENTAL

Preparation of Fibers

Sugar palm fibers or *ijuk* fibers, which is black and fibrous material that covers the trunk of sugar palm tree, were obtained from three different geographical locations, which were: (1) Kampung Kuala Jempol, Negeri Sembilan; (2) Kebun Rimau Sdn Bhd, Balung River, Tawau, Sabah; and (3) Kampung Naga, Tasikmalaya, Indonesia, as shown in Fig. 1. According to the website Weather Spark, the average weather in Kuala Jempol is hot, oppressive, and overcast and the temperature typically varies from 22 °C to 32 °C. For Tawau, the climate is warm, oppressive, and overcast and the temperature usually varies from 23 °C to 31 °C, while in Tasikmalaya, the climate is similar as in Tawau and the temperature typically varies from 20 °C to 31 °C.

In this experiment, a matured sugar palm tree (after undergoing flowering stage with age more than 6 years) with the height of 15 m was selected. The fibers were collected at the same part of the tree, which is the trunk. The fibers were washed and air dried for 24 h before being dried in the oven at 85 °C for another 24 h. All of these fibers were separated into plastic samples and labeled as SPF from Kuala Jempol, Tawau, and Indonesia.

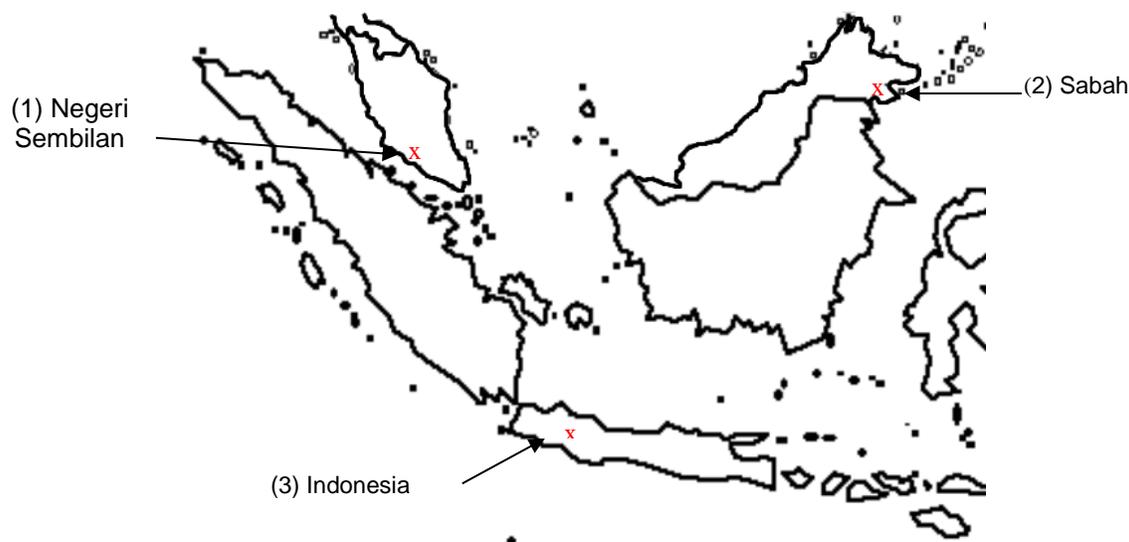


Fig. 1. Sugar palm fibers were obtained from three different geographical locations, which were: (1) Kampung Kuala Jempul, Negeri Sembilan; (2) Kebun Rimau Sdn Bhd, Balung River, Tawau, Sabah; and (3) Kampung Naga, Tasik malaya, Indonesia

Physical Characterisation

Density

The density of sugar palm fibers was determined using an AccuPyc[®] II 1340 TEC pycnometer (Micromeritics Instrument Corporation, Norcross, GA, USA). This automated pycnometer provides volume and density measurements according to ASTM D792 (2008). Three samples of fiber powder were used. Helium gas was used with constant temperature at 28.94 °C until equilibrium was reached. The pressure applied in this test was 134447.76 Pa.

Water absorption

Three samples were prepared, and each sample was replicated five times. The sample was weighed before (M_0) and after (M_1) being immersed in fresh water for 24 h at room temperature. The percentage of water absorption was determined by Eq. 1.

$$\text{Water absorption (\%)} = \frac{M_1 - M_0}{M_0} \times 100 \quad (1)$$

Moisture content

The moisture content was measured as previously described (Baley *et al.* 2012; Razali *et al.* 2015). Three samples were prepared, and each sample was replicated five times. The sample was weighed before (M_0) and after (M_1) being heated in an oven for 24 h at 105 °C. The moisture content was calculated by Eq. 2.

$$\text{Moisture content (\%)} = \frac{M_1 - M_0}{M_0} \times 100 \quad (2)$$

Diameter

The diameter of sugar palm fibers was measured using an optical microscope. Three samples with 10 replications of each sample were prepared, and the average diameters were recorded.

Thermal Characterization

Thermogravimetric analysis (TGA)

A thermogravimetric test was performed with a Universal V3.9A TA Instrument (New Castle, DE, USA) in the temperature range between room temperature and 600 °C at a heating rate of 10 °C/min in a nitrogen atmosphere. Ten mg of the sample was heated in the sample pan.

Chemical Characterization

The chemical composition of sugar palm fibers was analyzed by using neutral detergent fiber (NDF) and acid detergent fiber (ADF) (Nadlene *et al.* 2015; Jumaidin *et al.* 2017). This method evaluates the main fiber constituents including cellulose, hemicellulose, lignin, and ash. The percentage of cellulose and hemicellulose are determined using the equations below.

$$\text{Cellulose} = \text{ADF} - \text{lignin} \quad (3)$$

$$\text{Hemicellulose} = \text{NDF} - \text{ADF} \quad (4)$$

Tensile Characterization

The samples were selected randomly after being separated carefully from strand bundle of sugar palm fiber. To confirm that there was no damage on the fiber, the fibers were observed under optical microscope.

The tensile properties of sugar palm fibers were tested using an Instron 3365 apparatus according to ASTM D3379 (1998). The gauge length of the sample was 30 mm with a 5kN load cell, and the cross-head speed was 1 mm/min. The fiber was glued on the sample holder as shown in Fig. 2. Three samples of sugar palm fibers with 10 replicates for each sample were prepared to perform the test. Tensile strength of fibers was calculated as follows,

$$T = \frac{F}{A} \quad (5)$$

where T is tensile strength in Pa, F is force to failure in N, and A is average fiber area in m^2 .

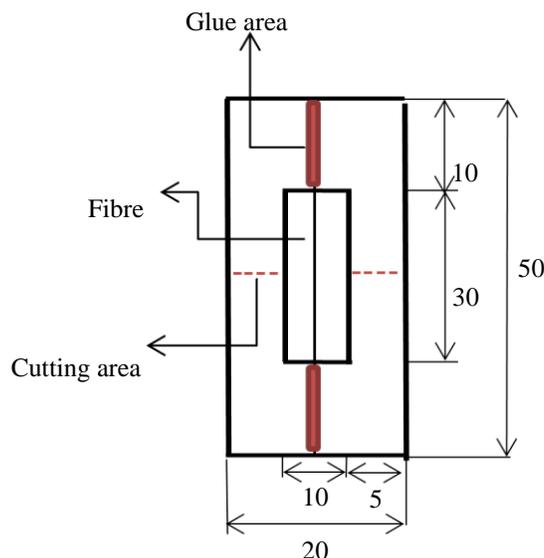


Fig. 2. Tensile test for SPF (Unit: mm)

Scanning Electron Microscope (SEM)

The morphology of the fiber surface was observed under scanning electron microscope (SEM) instrument model Hitachi S-3400N (Kyoto, Japan). In order to obtain cross-sectional morphology of sugar palm fibre, the fibres were immersed in liquid nitrogen to harden them. After that, the samples were coated with a thin layer of gold. The acceleration voltage used was 15 kV, and the distance to examine the sample was 50 mm.

Statistical Analysis

Statistical analysis of mechanical and physical properties was carried out by one-way analysis (ANOVA), and the significance of each mean property value was determined ($p \leq 0.05$) with Duncan's multiple range tests.

RESULTS AND DISCUSSION

Physical Properties of Sugar Palm Fibers

Density and diameter

Table 1 shows the physical properties of sugar palm fibers with respect to different geographical locations. The fiber from Tawau had the smallest fiber diameter of 0.349 ± 0.037 mm. The diameter of the fibers from Kuala Jempol and Indonesia were 0.4 ± 0.079 mm and 0.457 ± 0.095 mm, respectively as shown in Fig. 3. Although the fiber obtained from Indonesia had the largest diameter, under a microscope, the structure looked more brittle than the other fibers. According to Chandramohan and Marimuthu (2011), natural fiber do not have consistent properties because they depend on several factors. Reddy and Yang (2005) reported that factors that affect the physical properties were the source of the fiber, condition of the plant, maturity of the plant, and the extraction process.

The sugar palm density for fibers from Kuala Jempol, Tawau, and Indonesia was 1.4623 ± 0.0121 g/cm³, 1.4460 ± 0.009 g/cm³, and 1.4426 ± 0.0035 g/cm³, respectively. Thus, although the fiber obtained from Indonesia had the highest diameter, it had the lowest density. The density of sugar palm fiber is relatively low. According to Aziz and Ansell (2004) and Vilay *et al.* (2008), these properties are mainly affected by the presence of a lumen in the fiber structure. Lumen is a hollow structure with thin walls that contributes to natural fiber lightness. Table 2 shows the analysis of variance (ANOVA) of the physical properties. Statistically significant differences between the mean data from one level to another were evidenced by the P-value ($p < 0.05$).

Table 1. Physical Properties of Sugar Palm Fiber from Three Different Locations

Fiber	Tawau	Kuala Jempol	Indonesia
Diameter (mm)	0.349 ± 0.037	0.4 ± 0.079	0.457 ± 0.095
Density (g/cm ³)	1.4460 ± 0.009	1.4623 ± 0.0121	1.4426 ± 0.0035
Water absorption (%)	156.56 ± 19.64	161.96 ± 34.04	80.32 ± 13.3
Moisture content (%)	7.05 ± 1.62	6.45 ± 1.07	5.63 ± 0.4

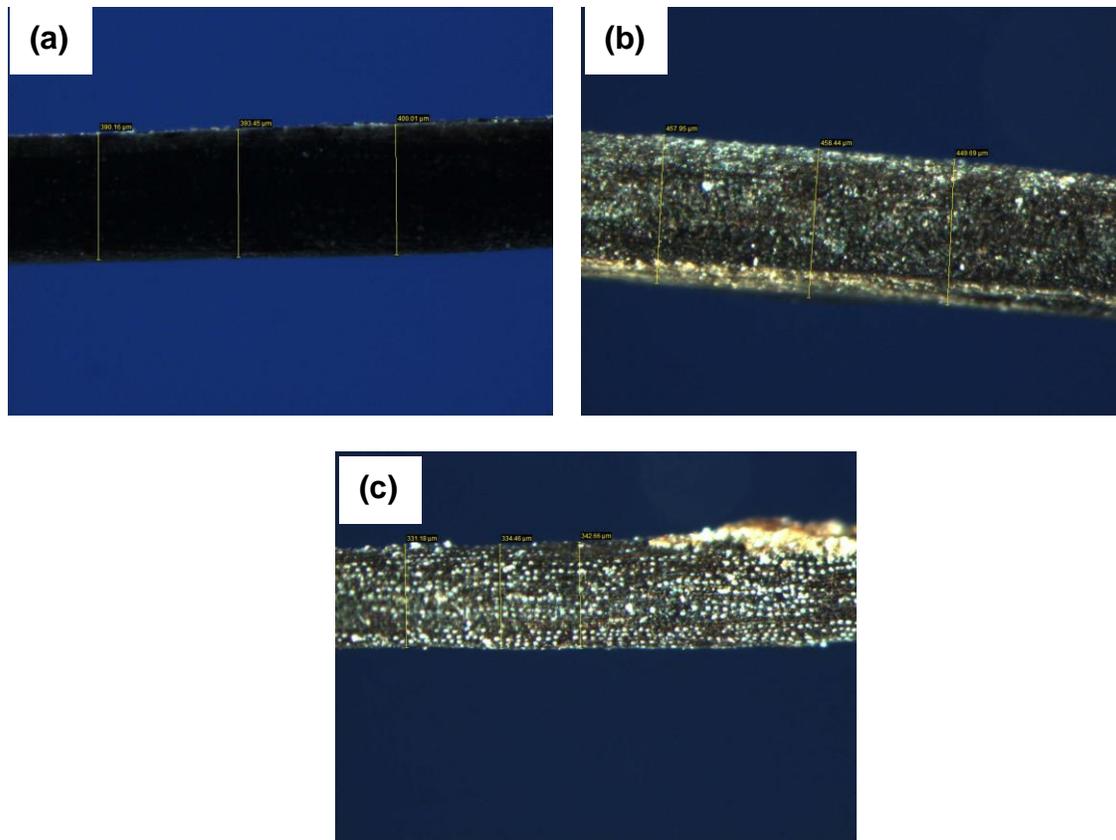


Fig. 3. Diameter measurement of SPF from (a) Kuala Jempol, (b) Indonesia, and (c) Tawau

Table 2. Summary of the Analysis of Variance (ANOVA) of Physical Properties

Variable	df	Diameter	Density	Water absorption	Moisture content
Mixture	2	0.12*	0.00*	0.00*	0.003*

*Note: Significantly difference at $p \leq 0.05$.

Water absorption

As shown in Table 1, the Kuala Jempol fiber had the highest value of water absorption ($161.96 \pm 34.04\%$), followed by Tawau ($156.56 \pm 19.64\%$) and Indonesia ($80.32 \pm 13.3\%$). The water absorption test was calculated based on weight of the sample before and after soaking in water for 24 h. Natural fibers are hydrophilic, which affects the value of water absorption and moisture content (Sahari *et al.* 2011). Moreover, the high water absorption of natural fibers makes it difficult to obtain good adhesion between the fiber and the matrix, leading to poor properties in the composite product (Nguong *et al.* 2013). All lignocellulosic materials consist of cellulose, hemicellulose, and lignin that contribute to water absorption behavior. These elements contain many -OH groups that attract water molecules. Sahari *et al.* (2011) have shown that there are relationships between holocellulose content and water absorption. The results in Table 3 show that the fiber obtained from Kuala Jempol had the highest holocellulose content, which was 54.54%, which in turn allowed for the greatest water absorption, followed by the fibers obtained from Tawau and Indonesia (Fig. 4).

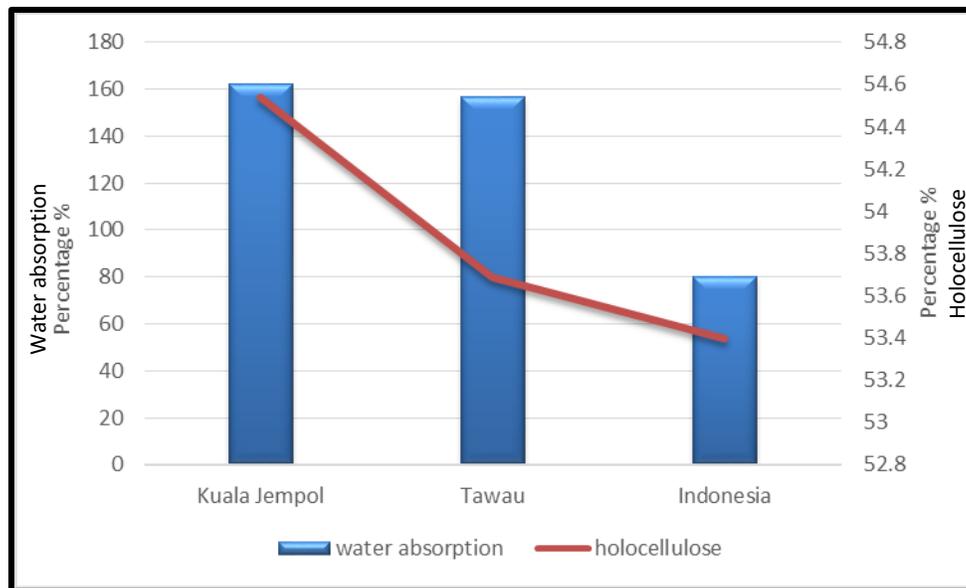


Fig. 4. Water absorption and holocellulose percentage of sugar palm fibers from different geographical locations

Moisture content

Moisture content must be a consideration when using natural fibers as a reinforcement in material composites. As shown in Table 1, the Tawau fiber recorded the highest moisture content, which is $7.05 \pm 1.62\%$ followed by Kuala Jempol ($6.45 \pm 1.07\%$) and Indonesia ($5.63 \pm 0.4\%$). The moisture content of natural fibers affects their dimensional stability, electrical resistivity, tensile strength, porosity, and swelling behavior (Razali *et al.* 2015). In cellulosic/synthetic fiber reinforced polymer hybrid composites, the most desirable criteria is low moisture content (Jawaid and Abdul Khalil 2011). Moreover, composites with high moisture content fibers may experience degradation due to retained water (Rowell *et al.* 2000).

Chemical Properties

Chemical composition affects the physical, mechanical, and thermal properties of a natural fiber. Natural fibers consist of cellulose, hemicellulose, pectin, lignin, ash, and other naturally occurring constituents (Rong *et al.* 2001; Kalia *et al.* 2009). Lignocellulose contains hemicellulose, cellulose, and lignin, which comprise 10 wt.% to 25 wt.%, 31 wt.% to 70 wt.%, and 7 wt.% to 26 wt.%, respectively (McKendry 2002; Li *et al.* 2007; Yang *et al.* 2007). Table 3 shows the chemical composition of sugar palm fiber obtained from the three different geographical locations.

Sugar palm fibers have a high cellulose content of more than 40%. The fiber with the highest cellulose content was obtained from Kuala Jempol (44.53%), followed by Indonesia (44.47%) and Tawau (43.75%). Cellulose is the main structural component that gives mechanical strength to the stem plant cell wall and strength to the fiber (Reddy and Yang 2005). Changes in the cellulose content may affect the fiber properties, applications, and production cost. Higher cellulose content contributes to greater fiber strength, which makes it preferable for textile, paper, and other fibrous applications (Fávaro *et al.* 2010).

Table 3. Chemical Composition for Selected Natural Fiber

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Reference
SPF/ Kuala Jempol	44.53	10.01	41.97	0.955	Current study
SPF/ Indonesia	44.47	8.93	41.425	0.91	Current study
SPF/ Tawau	43.75	9.94	39.54	1.34	Current study
Kenaf	31-63.5	17.6-23	12.7-19	2-5	Li <i>et al.</i> 2007; Jonoobi <i>et al.</i> 2009
Jute	45-71.5	13.6-21	13.26	0.5-2	Li <i>et al.</i> 2007; Wang <i>et al.</i> 2008
Hemp	55-77	14-22.4	3.7-13	0.8	Li <i>et al.</i> 2007; Sathishkumar <i>et al.</i> 2013
Flax	64-71.9	16.7-20.6	2-2.2	-	

Hemicellulose is composed of polysaccharide polymers where the orientation and degree of polymerization are lower than for the cellulose (Sathishkumar *et al.* 2013). Hemicellulose consists mainly of glucose, xylose, galactose, arabinose, and mannose sugar units (Reddy and Yang 2005). Compared with cellulose, hemicellulose is easier to hydrolyze into sugar. To produce ethanol and other fermentation products, a high hemicellulose content is preferable compared with other constituents. Hemicellulose does not contribute to reinforcing the fiber, but it acts as a binder of microfibrils and provides structural reinforcement for microfibrils.

Lignin is amorphous and has aromatic rings with various possible branches. It acts as glue between individual cells and between the fibrils forming the cell wall. Lignin is first formed between neighboring cells in a middle lamella, bonding them tightly into a tissue, and then spreads into the cell wall, penetrating the hemicellulose and bonding the cellulose fibrils. Lignin provides plant tissue and individual fibers with compressive strength and stiffness to the cell wall to protect the carbohydrate from chemical and physical damage. The lignin content influences the structure, properties, morphology, flexibility, and rate of hydrolysis (Reddy and Yang 2005).

Tensile Properties

The sugar palm fibers (Kuala Jempol, Tawau, and Indonesia) were tested, and their strength strain behavior is shown in Fig. 5. From the curve, it is apparent that the strength increased with the increase of strain value and then experienced failure at a certain point. According to Ishak *et al.* (2012), the failure may be attributed to poor strength of fiber when the fiber is pulled under the action of applied forces.

Table 4 compares the tensile properties of sugar palm fiber and several selected fibers. Several variables affect the properties of natural fibers, including cell dimension, structure, micro-fibril angle, chemical composition, and defects (Ishak *et al.* 2012). These variables need to be identified before fibers are used as reinforcement materials.

The tensile strength, elongation at break, and modulus of sugar palm fiber from different locations are compared in Figs. 6 through 8. Kuala Jempol fiber had the highest average tensile strength, 233.28 ± 71.17 MPa, while Indonesia and Tawau fibers were

219.30 \pm 79.71 MPa and 211.04 \pm 81.19 MPa, respectively. These results are compatible with the cellulose content of the fibers shown in Table 3 (*i.e.*, Kuala Jempol fiber had the highest cellulose content, 44.5%, while Indonesia and Tawau were 44.5% and 43.8%, respectively), where the highest cellulose content had the highest strength properties. Ishak *et al.*(2012), Razali *et al.*(2015), and Reddy and Yang (2005) agree that cellulose is the main structural component providing mechanical strength and stability to the fiber.

Tensile modulus shows the capability of the fiber to resist deformation when stress is applied. As shown in Fig. 7, Tawau fiber had the highest average tensile modulus, 4324.82 \pm 1788.61 MPa, while Kuala Jempol and Indonesia were 4189.47 \pm 1616.11 MPa and 3889.02 \pm 1516.66 MPa, respectively. For the elongation at break, Tawau fiber had the lowest percentage, which was 15.87 \pm 6.82% as shown in Table 4, while the percentage of elongation at break for sugar palm fibers from Kuala Jempol and Indonesia were 20.63 \pm 9.29% and 20.43 \pm 9.29%, respectively. As shown in Table 5, there were no significant differences between mechanical properties of sugar palm fiber obtained from the three different geographical locations.

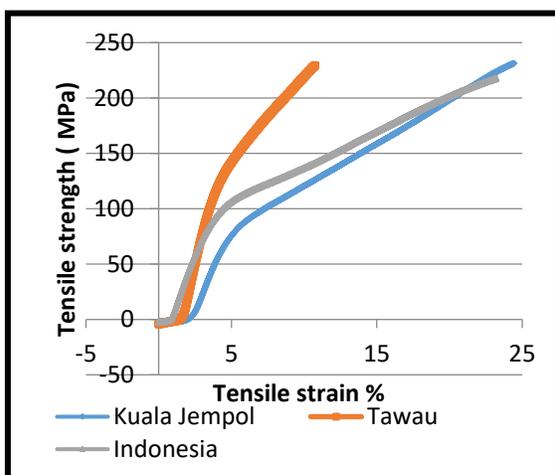


Fig. 5. Tensile strength-strain of sugar palm fibers from different geographical locations

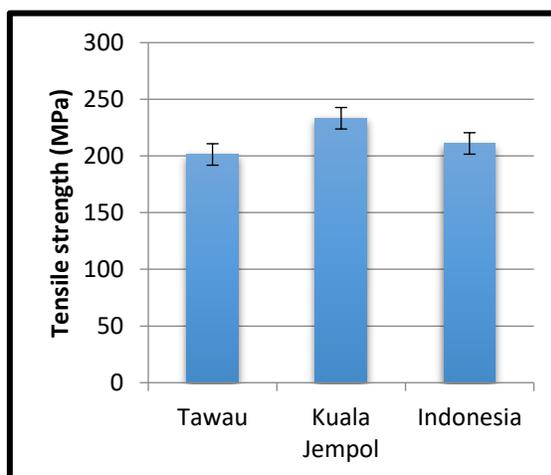


Fig. 6. Tensile strength of sugar palm fibers from different geographical locations

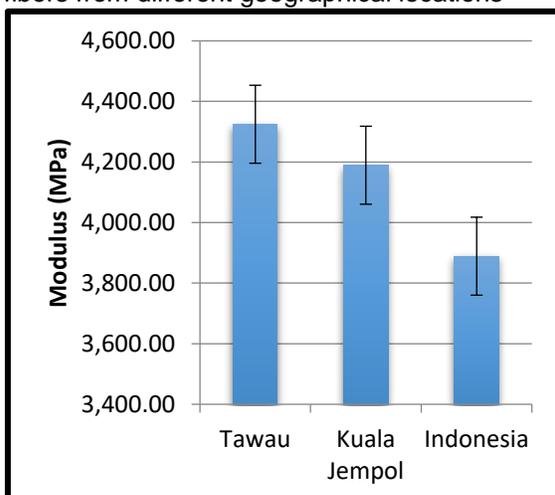


Fig. 7. Tensile modulus of sugar palm fibers from different geographical locations

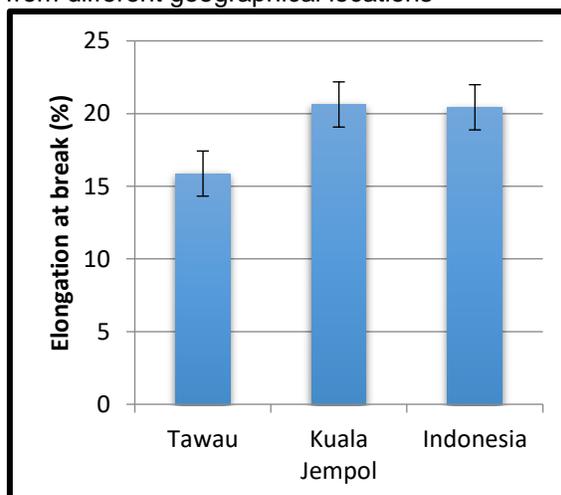


Fig. 8. Elongation at break of sugar palm fibers from different geographical locations

Table 4 compares the tensile properties of sugar palm fiber with other bast fibers such as cotton, ramie, hemp, jute, sisal, kenaf, and coir fibres. Sugar palm fiber has good tensile strength compared with other established bast fibers.

Table 4. Tensile Properties for Selected Natural Fibers

Fiber	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)	Reference
SPF/ Kuala Jempol	233 ±71.17	4.189 ±1.61	20.6 ±9.29	Current study
SPF/ Indonesia	219 ±79.71	3.889 ±1.78	20.4 ±9.29	Current study
SPF/ Tawau	211 ±89.19	4.324 ±1.15	15.8 ±6.82	Current study
Cotton	287-597	5.5-12.6	3-10	(Satyanarayana <i>et al.</i> 1990; Li <i>et al.</i> 2007)
Ramie	220-938	44-128	2-3	(Li <i>et al.</i> 2007)
Hemp	550-900	70	1.6	(Li <i>et al.</i> 2007)
Jute	393-800	10-30	1.5-1.8	(Li <i>et al.</i> 2007); Rao <i>et al.</i> 2007)
Sisal	227-400	9-20	2-14	(Rao <i>et al.</i> , 2007); Silva <i>et al.</i> 2008; (Fávaro <i>et al.</i> , 2010)
Kenaf	250	4.3	-	(Lee <i>et al.</i> 2009)
Coir	108-215	4-6	15-40	(Rao <i>et al.</i> 2007)

Table 5. Summary of the Analysis of Variance (ANOVA) of Mechanical Properties

Variable	df	Tensile strength	Tensile modulus	Elongation
Mixture	2	0.654*	0.838*	0.415*

*Note: Significant different at $p \leq 0.05$.

Thermal Properties of SPF

TGA is a method to determine the changes of the weight of a material as a function of the temperature under a controlled atmosphere. It is important to determine the degradation temperature of natural fibers before the manufacturing process, in order to know the fibers' resistance to high temperatures. Thermal properties have significant effects on the behavior of the fiber and composites. Low thermal stability is one of the limiting factors to using natural fiber as reinforcements in bio-composites. Table 6, Table 7, Fig. 9, and Fig. 10 present the characteristic data of thermal properties of sugar palm fiber at high temperatures obtained from three different locations. According to Ishak *et al.* (2012), there are four phases of thermal decomposition: moisture evaporation (45 °C to approximately 123 °C), followed by the decomposition of hemicelluloses (210 °C to 300 °C), cellulose (300 °C to 400 °C), lignin (160 °C to 900 °C), and finally ash. These temperature ranges are used to determine the capability of fiber to withstand the temperature applied during the manufacturing process or application of the product.

The first decomposition of natural fiber takes place between 30 °C to 110 °C (De Rosa *et al.* 2010). In this study, moisture evaporation in sugar palm fiber occurred from 30 °C to 110 °C. In this phase, the fiber burns slowly, and the increased temperature

makes the fiber become lighter due to the evaporation of the water-bound and volatile extractives. Although a small amount of volatile extractives remain in the inner fiber, they tend to move toward the outer layer of the fiber due to the water available at the outer layer being evaporated. Thus, the volatile extractives are carried by water and remain on the outer layer of the fiber. As shown in Table 6, the weight loss of fibers from Kuala Jempol (11.9%) and Indonesia (11.2%) were not obviously different from those obtained from Tawau (15.0%). Figure 9 graphs the weight loss for sugar palm fiber as the temperature increased, which reflects the moisture content of the sugar palm fibers.

Table 6. Thermal Degradation Analysis of Sugar Palm Fiber

Sugar Palm Fiber Location	Weight Loss (%) from 30 to 110 °C	First Degradation Phase			Second Degradation Phase			Char Residue (wt.%)
		T_1 (°C)	Weight loss (%)	T_{peak} (°C)	T_2 (°C)	Weight loss (%)	T_{peak} (°C)	
Tawau	14.99	140-280	14.63	249.95	290-340	43.56	321.36	26.81
K. Jempol	11.90	150-260	15.10	251.36	280-350	44.24	324.28	28.77
Indonesia	11.19	160-250	15.22	246.93	300-350	45.12	326.89	28.45

The second phase represented hemicellulose decomposition. Hemicellulose starts to decompose at 220 °C and decomposes completely at 315 °C. In sugar palm fiber obtained from Tawau, hemicellulose decomposition occurred between 140 °C to 280 °C. The fibers obtained from Kuala Jempol and Indonesia started to decompose at 150 °C to 260 °C and 160 °C to 250 °C, respectively. According to Ishak *et al.* (2012), hemicellulose is the first component to decompose because its structure contains heterogeneous polysaccharides such as galactose, glucose, mannose, and xylose. Polysaccharides are very amorphous in nature and have many branches making them very easy to remove from the main stem at the lower temperatures, and they are volatile (Yang *et al.* 2007; Ishak *et al.* 2012). Thus, hemicellulose is less thermally stable than cellulose. Cellulose has a higher content of crystalline structure of about 80%, which is the primary reinforcement in the cell wall (Ho *et al.* 2012).

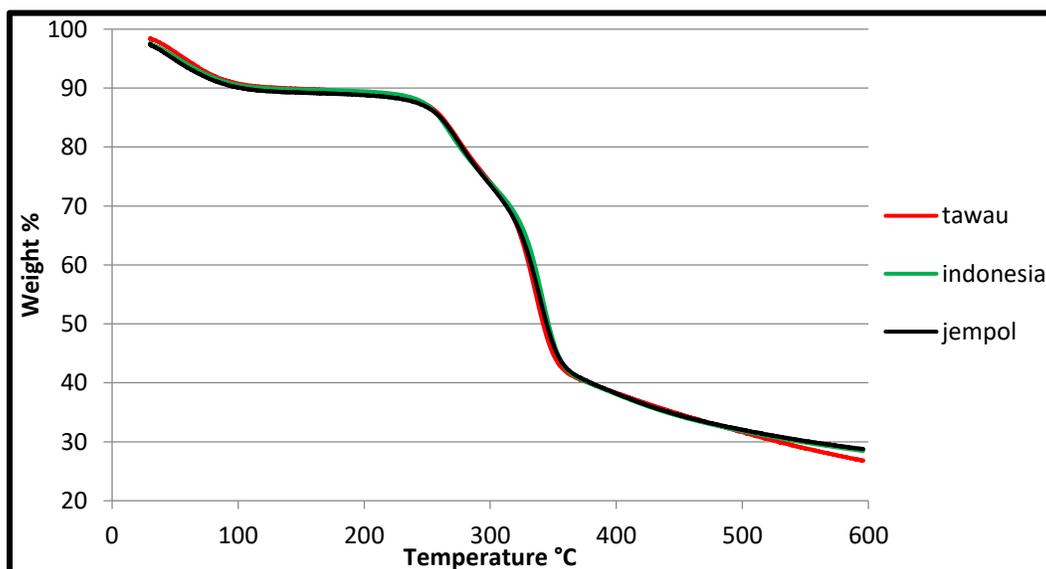


Fig. 9. Thermogravimetric analysis of sugar palm fibers from different locations

In the third phase, cellulose was decomposed. Cellulose decomposition does not begin until hemicellulose has completely decomposed, which is normally around 315 °C (Yang *et al.* 2007). For all sugar palm fiber samples, cellulose decomposition started at 280 °C and was completed at 350 °C. When the sample was heated to the target temperature, the mass decreased rapidly. The percentage mass loss for sugar palm fiber obtained from Tawau, Kuala Jempol, and Indonesia was 43.6%, 44.2%, and 45.1%, respectively.

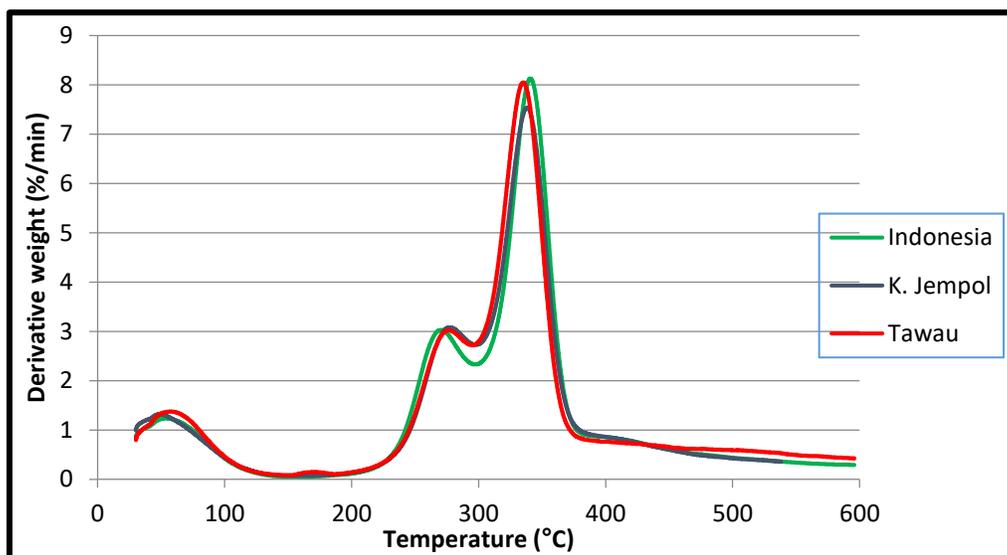


Fig. 10. DTG of sugar palm fibers from different geographical locations

The DTG graph in Fig. 10 indicates that the degradation of crystalline cellulose occurred from 280 °C to 330 °C, with the average highest peak temperature of decomposition occurring at 325 °C. This result confirms the report by Kim *et al.* (2001) that the decomposition of cellulose occurs at 300 °C and the critical temperature of crystalline cellulose decomposition is 320 °C.

The last component that decomposes is lignin because it has a relatively complex structure. The complexity is further defined by aromatic rings with various possible branches (Vonholme *et al.* 2010). Figure 9 show that lignin degraded slowly within the whole range of temperatures. It is hard to decompose lignin structure due to its complexity, and because of that it is difficult to see the peak of lignin. According to Ishak *et al.* (2012) lignin begins to decompose as early at temperature 160 °C, and the complete decomposition of lignin is complete at 900 °C (Yang *et al.* 2007). Lignin is a very tough component that provides rigidity to the plant materials. It is also provides stiffness to the cell wall and bonds individual cells together in the middle lamella region (Vonholme *et al.* 2010).

Table 7 shows that sugar palm fiber did not have major differences with other bast fibers in terms of decomposition temperature. Thus, sugar palm fiber is as thermally stable as other established bast fibers such as jute and kenaf.

Table 7. Decomposition Temperature for Selected Natural Fibers

Natural Fiber	Temperature of Initial Decomposition (°C)	Maximum Decomposition Temperature (°C)	References
Sugar palm	228	312	Ishak <i>et al.</i> 2012
Flax	220	339.4	Van De Velde and Baetens 2001
Okra	220	390	De Rosa <i>et al.</i> 2010
Kenaf	219	284	De Rosa <i>et al.</i> 2010
Jute	205	283	De Rosa <i>et al.</i> 2010
Hemp	250	390	De Rosa <i>et al.</i> 2010
Curaua	230	335	Spinacé <i>et al.</i> 2009
Roselle	210	366.08	Razali <i>et al.</i> 2015

Morphological Properties

The surface morphology of the sugar palm fiber was analyzed using SEM (Fig. 11). Morphological properties indicate the behavior of natural fiber before they become reinforcement in composite materials because they affect the physical and mechanical properties (Munawar *et al.* 2007). In addition, the changes in morphology are important to predict fiber interactions with polymer matrices in composites.

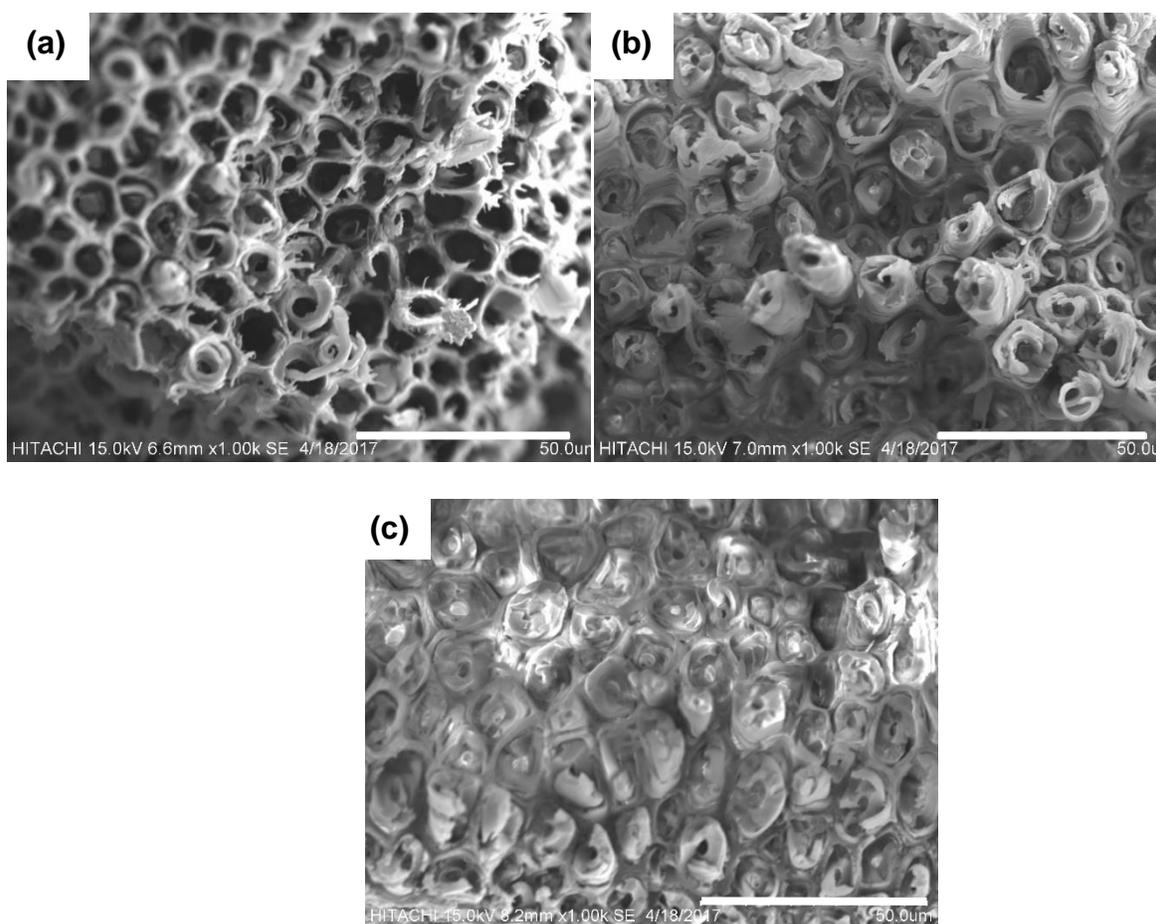


Fig. 11. SEM of cross section of SPF from (a) Kuala Jempol, (b) Indonesia, and (c) Tawau

Figure 11 shows SEM cross sections of sugar palm fibers from different locations. The lumen structure of the sugar palm fiber can be seen clearly in Fig. 11. The lumen size influences the water uptake, and thus, the moisture content (Yusriah *et al.* 2014; Razali *et al.* 2015); larger lumen structures allow the fiber to absorb more water.

CONCLUSIONS

The physical, chemical, tensile, thermal, and morphological properties of sugar palm fiber obtained from three different locations (Kuala Jempol, Indonesia, and Tawau) were evaluated. Based on the ANOVA results, there were no significant difference among fiber obtained from three different geographical location ($p > 0.05$). However, the fiber from Kuala Jempol showed the highest cellulose content, which contributed to greater tensile strength and thermal stability of the fiber. The moisture content and water absorption of the sugar palm fiber obtained from Indonesia had the lowest value compared with the other fibers. Fiber from Kuala Jempol had best performance for composite manufacturing.

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