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Review

# Sugar palm (*Arenga pinnata*): Its fibres, polymers and composites

M.R. Ishak[a,*], S.M. Sapuan[a,b,c], Z. Leman[a], M.Z.A. Rahman[d], U.M.K. Anwar[c,e], J.P. Siregar[a]

[a] *Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[b] *Institute of Advanced Technology (ITMA), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[c] *Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[d] *Centre of Foundation Studies for Agricultural Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[e] *Wood Finishing Laboratory, Forest Research Institue of Malaysia (FRIM), Kepong, Kuala Lumpur, Malaysia*

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ABSTRACT

Sugar palm (*Arenga pinnata*) is a multipurpose palm species from which a variety of foods and beverages, timber commodities, biofibres, biopolymers and biocomposites can be produced. Recently, it is being used as a source of renewable energy in the form of bio-ethanol via fermentation process of the sugar palm sap. Although numerous products can be produced from sugar palm, three products that are most prominent are palm sugar, fruits and fibres. This paper focuses mainly on the significance of fibres as they are highly durable, resistant to sea water and because they are available naturally in the form of woven fibre they are easy to process. Besides the recent advances in the research of sugar palm fibres and their composites, this paper also addresses the development of new biodegradable polymer derived from sugar palm starch, and presents reviews on fibre surface treatment, product development, and challenges and efforts on properties enhancement of sugar palm fibre composites.



**Contents**



## 1. Introduction

In recent years, issues of climate changes, global warming, deforestation, non degradable waste materials, water and air pollutions have become major concerns to the entire mankind. These concerns have forced scientists and engineers to search for solutions that would ensure the preservation of sustainable forests and green environment.

Several factors have contributed to the intensity of research in recent years on the use of natural fibre to reinforce polymer composites. Firstly, their use can contribute to the supply of raw materials (natural fibres) and to some extent, reduce the dependence on the usage of timbers. Also, the use of natural fibres in the reinforcement of composites would result in partial degradation of the unused products, which in turn, can partially solve environmental problems. The unused natural fibre composites can be recycled by crushing them into particles and remanufacturing them

* Corresponding author. Tel.: +60 133689132; fax: +60 386567122.
*E-mail address:* mridhwanishak@yahoo.com (M.R. Ishak).

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**Fig. 1.** Sugar palm tree (Sapuan et al., 2010).

to form new particle composite boards. Specific strength and modulus of natural fibre composites are equivalent to many conventional fibre composite materials. In addition, the consideration of using sugar palm as reinforcement in composites is based not only on its excellent properties of fibres, but also on its contribution to the conservation of forestry, biodiversity, utilisation of plant waste and to availability of fibres abundantly at a very low cost.

Tropical countries like Malaysia and Indonesia are homes to many types of natural fibres. One of them is sugar palm (*Arenga pinnata*) fibre. However, little research has been done to date on the significance of sugar palm fibre and its composites. This paper reviews the literature on the latest advances in research on sugar palm fibres, polymer from sugar palm and their composites. It also investigates the recent product development as well as the challenges and efforts made on enhancing the properties of sugar palm fibres composites. This paper also attempts to explore other potential uses of sugar palm and its fibre composites to further develop sugar palm trees as a new crop in the near future.

## 2. Sugar palm plant

### 2.1. History of sugar palm

Sugar palm (Fig. 1) belongs to the sub-family of Arecoideae and the tribe of Caryoteae (Dransfield & Uhl, 1986; Moore, 1960). It was earlier given a number of taxonomic names such as *Saguerus rumphii* and *Arenga saccharifera Labill*. However, in 1917 during the International Congress of Botany in Vienna, it was officially renamed as *Arenga pinnata*. Sugar palm is a natural forest species that originates from the Palmae family. It is known as a fast growing palm that is able to reach maturity within 10 years (Mogea, 1991). Hyene (1950) reported that there are approximately 150 local names of sugar palm tree in Indonesia while in Malaysia, it is known as either *enau* or *kabung*. Geographical distribution of sugar palm trees covers as wide as South Asia to South East Asia and Taiwan to the Philippines, Indonesia, Papua New Guinea, India, Thailand, Myanmar, Vietnam, North Australia and Malaysia (Miller, 1964; Ismail, 1994; Sapuan, Ishak, & Bachtiar, 2010).

### 2.2. Multipurpose of sugar palm

Sugar palm is one of the most versatile palm species because almost all parts of the tree can be used, with the palm sap being the most important product (Siregar, 2005). Apart from the palm sap, other significant products that can be produced from sugar palm include palm neera, fresh juices, traditional sugar blocks, toddy, crystal and brown sugar (Mogea, Seibert, & Smits, 1991), vinegar (Redhead, 1989), bio-ethanol (Lay, 2009), starch from trunk, sea water resistant fibre, edible heart (Mogea et al., 1991), fruits, leaves for roofing, brooms, matting, baskets, cigarette papers (Johnson, 1987), cattle feeds (Sath, Borin, & Preston, 2008) and its starch inside the stem can be processed to make biopolymer. The palm sugar can be consumed fresh or can be cooked to make traditional sugar blocks as ingredient in making cakes, desserts and food coating (Ho, Wan Aida, Masket, & Osman, 2008). It can also be processed to crystal and brown sugar and used as an alternative to the commercialised sugarcane granular sugar (Ishak, Sapuan, Leman, Sahari, & Ibrahim, 2010a). Although sugar palm has magnificent properties, the work on sugar palm has been restricted to the activity of tapping the palm sap for the production of traditional sugar blocks called *gula enau* or *kabung* and neera syrup. There are thousands of farmers in Indonesia and Malaysia (Kuala Pilah and Jempol, Negeri Sembilan; Kuala Lipis, Pahang; Tawau, Sabah; etc.) who earn a living by tapping sugar palm sap.

### 2.3. Bio-ethanol from sugar palm

Nevertheless, in the recent years the use of palm sugar has advanced to another level since palm sugar can now be fermented with yeast to produce alcoholic beverages. Bio-ethanol is used as raw material for products such as chemical products, solvents, pharmaceutical, cosmetics, medicines and beverages. Palm sugar can also be used for the production of bio-fuel as a renewable source of energy like other bio-ethanol plant sources (Ishak et al., 2010a). It is interesting to note that sugar palm can yield the highest productivity of bio-ethanol (20,160 l/ha/year) compared to other sources such as cassava (4500 l/ha/year), sugarcane (5025 l/ha/year), sago (4133 l/ha/year), and sweet sorghum (6000 l/ha/year) (Allorerung, 2007). A large scale commercialisation of sugar palm plantations which is as wide as 800,000 ha to 4,000,000 ha are in the process of development, especially in Indonesia to make use of this tremendous potential of sugar palm plants.

## 3. Sugar palm fibre

Another important product of the sugar palm is its fibre. It has several names such as Aren, gomuti, and black and locally it is known as the *ijuk* fibre. The commercialisation of sugar palm fibre can be tracked back as early as 1416 during the Malacca Sultanate era. Later in 1800, sugar palm was planted by British East India Company in Penang to produce high durability rope made from its fibre (Othman & Haron, 1992). This multipurpose fibre can be used to make a number of products such as ropes, filters, brushers, brooms, mats, cushions and shelters for fish breeding (Mogea et al., 1991). According to Haris (1994), fibre is the most important constituent of in sugar palm tree in the Philippines.

Sugar palm fibres are known for their high durability and their resistance to sea water. These two characteristics are the main advantages of sugar palm fibre. Traditionally, sugar palm fibres were used to make ropes for ship cordages which were proven to have good properties in sea water. Other than that, the preparation

**Table 1**
Tensile properties and toughness of sugar palm fibre obtained from different heights of sugar palm tree (Ishak, Sapuan, Leman, Rahman, & Anwar, 2011).

| Height (m) | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 |
|---|---|---|---|---|---|---|---|---|
| Tensile strength (MPa) | 15.5 | 81 | 149 | 201 | 266 | 292 | 279 | 270 |
| Tensile modulus (GPa) | 0.49 | 1.15 | 1.97 | 2.76 | 3.22 | 3.34 | 3.37 | 2.68 |
| Elongation at break (%) | 5.75 | 12.54 | 27.75 | 28.32 | 24.68 | 23.08 | 21 | 18.80 |
| Toughness ($MJ/m^3$) | 0.58 | 7.36 | 33.58 | 46.09 | 50.64 | 52.46 | 45.21 | 35.71 |

for sugar palm fibres is effortless as the fibres do not require any secondary processes such as water retting or mechanical decorticating process to yield the fibre. This is due to the fact that the fibres, originally wrapped around the sugar palm trunk from the bottom to the upper part of the tree, are in the form of natural woven fibre (Ishak, Leman, Sapuan, Salleh, & Misri, 2009; Ishak et al., 2010a; Ishak, Sapuan, Leman, Rahman, & Anwar, 2012a; Ishak, Leman, Sapuan, Rahman, & Anwar, 2012b; Ishak, 2009).

The tree begins to produce fibre before flowering approximately after five years of plantation. The fibre is black and its length is up to 1.19 m. Its diameter ranges between 94 and 370 μm and its density is 1.26 $kg/m^3$ (Bachtiar, Sapuan, Zainudin, Khalina, & Dahlan, 2010). According to Harpini (1986), the fibre's strength is influenced by the age and altitude of sugar palm tree. It is heat resistant up to 150 °C with a flash point at around 200 °C (Ismail, 1994; Siregar, 2005). It is sorted into five grades from *A* to *E*, with grade *E* being the best as it has the longest and thickest fibres (Anon., 2008). Bachtiar, Sapuan, Zainudin, Khalina, and Dahlan, 2010 reported the tensile strength, tensile modulus and elongation at break of sugar palm fibre to be 190.29 MPa, 3.69 GPa, and 19.6%, respectively.

Further characterisation on tensile properties of sugar palm fibres was conducted by Ishak, Sapuan, Leman, Rahman, and Anwar (2011). The fibres were obtained from different heights of sugar palm tree (1, 3, 5, 7, 9, 11, 13, and 15 m) and tested for single fibre tensile test. The results showed that the fibres obtained from bottom part demonstrated inferior properties of tensile strength, modulus, elongation at break and toughness compared to fibres obtained at the area of live palm frond. It is also found that tensile strength, modulus, elongation at break and toughness of fibres obtained from the upper part (13 and 15 m) slightly decreased compared to fibres obtained at the area of live palm frond (Table 1).

It was concluded by Ishak, Sapuan, Leman, Sahari, and Ibrahim (2010d) that the differences in tensile properties of these fibres were due to the differences in of their chemical composition. They also added that ageing was occurred and affecting the chemical composition of its fibre especially at the bottom part of the tree. For the fibre obtained from 1 m height, it is believed that polymeric chains in microfibrils were broken and had lower contents of cellulose, hemicelluloses and lignin (37.3%, 4.71%, 17.93%, respectively) (Table 2) as compared to the fibres obtained from at the area of live palm frond. It was observed that the cellulose, hemicelluloses, and lignin contents increased with an increase of the tree height up to 5 m height (53.41–56.8%, 7.45–7.93%, 20.45–24.92%, respectively) where beyond this height (5 m), it remained unchanged.

Since the fibre of 1 m height was very close to the ground, it contains a lot of impurities such as silica as evident from much higher ash content (30.92%) compared to the fibres obtained from upper parts (5–15 m) where the ash content is in the ranges of 2.06–5.84% (Table 2). Due to their significantly high ash content, it is observed that the fibre of 1 m height has lower moisture content (5.36%) than other fibres (3–15 m height), which were in the range of 7.72–8.7%.

The Fourier transform infrared (FT-IR) spectra of these fibres were also studied and revealed that the relative absorbances, representing amounts of different functional groups in sugar palm fibres, were essentially the same regardless of different heights. In this study, it is worth mentioning that the mechanical properties of sugar palm fibre had a good correlation to their chemical composition. It was observed that their cellulose, hemicelluloses and lignin show a significant contribution to the increase in tensile strength, elongation at break, and modulus of the fibre, respectively.

Thermogravimetric (TGA) analysis of these fibres (1, 3, 5, 7, 9, 11, 13, and 15 m) was also characterised (Ishak, Sapuan, Leman, Rahman, & Anwar, 2011). It was observed that there were four phases of decomposition of the fibres where the sequence of decomposition started with evaporation of moisture and followed by decomposition of hemicelluloses, cellulose, lignin while the last component left was their ash. The thermal degradation of these components were found in ranges of 45–123, 210–300, 300–400, 160–900 and 1723 °C, respectively. It was also observed that TG/DTG curves showed that the fibre of 1 m showed higher thermal stability than the fibres of 3–15 m which was attributed to the high ash content.

Sahari, Sapuan, Ismarrubie, and Rahman (2012) studied tensile properties of sugar palm (*ijuk*) fibre and compared it with fibres obtained from different parts of sugar palm tree namely the frond, trunk and bunch fibres. The results (Table 3) showed that the highest tensile properties (tensile strength, tensile modulus and elongation at break) were obtained at frond fibre followed by bunch fibre, *ijuk* fibre and lastly at trunk fibre. These results are in good agreement with their chemical compositions in the same study since the mechanical properties of natural fibres are strongly influenced by their cellulose content (Habibi, El-Zawawy, Ibrahim, & Dufresne, 2008) that provides strength and stability to the cell walls of fibres (Reddy & Yang, 2005). The results indicated that the highest cellulose content was found in frond fibre followed by bunch fibre, then by *ijuk* fibre and finally by trunk fibre whereby these show a good agreement with their tensile strength.

The results found in Bachtiar, Sapuan, Hamdan, and Sastra (2006) were similar in which the cellulose content was 50%, while hemi-cellulose, lignin, ash, and moisture contents were 7, 45, 3–7, and 9.5%, respectively. The FT-IR spectra for all 4 types of sugar palm fibre i.e. SPB, SPF, *ijuk* and SPT was also analysed (Sahari et al., 2012). It was observed that the spectra were almost the same among the 4 types of fibre and no major differences observed if the spectra with other established fibres.

## 4. Sugar palm fibre composites

To date, the use of sugar palm fibre has moved to another successive level specifically to various engineering applications. For example, it has been used in road constructions for soil stabilisation as a substitute for geo-textile fibreglass reinforcement. Apart from that, in certain circumstances, it is also being used for underwater and underground cables (Siregar, 2005). In the field of material engineering, it is being used as reinforcement in polymer matrix composites. Several studies have shown that sugar palm fibres have great potential to be used in many composite applications, just like other natural fibres such as kenaf, jute, oil palm, sugarcane bagasse, pineapple leaf and banana pseudo stem fibres (Abdullah & Sastra, 1999; Bachtiar et al., 2006; Bachtiar, Sapuan, Zainudin, Khalina, et al., 2010; Mogea et al., 1991; Sahari, Sapuan, Rahman, Ishak, & Ibrahim, 2010a; Sahari et al., 2012; Sarjono & Wajono, 2008). A number of studies on the properties of sugar palm fibre composites

**Table 2**
Chemical compositions of sugar palm fibre obtained from different heights of sugar palm tree (Ishak et al., 2010d).

| Height (m) | 1 | 3 | 5 | 7 | 9 | 11 | 13 | 15 |
|---|---|---|---|---|---|---|---|---|
| Holocellulose (%) | 43.3 | 56.36 | 64.28 | 65.55 | 64.8 | 63.75 | 62.42 | 57.41 |
| Cellulose (%) | 37.3 | 49.36 | 55.28 | 56.55 | 56.8 | 55.75 | 54.42 | 53.41 |
| Hemicelluloses (%) | 4.71 | 6.11 | 7.36 | 7.68 | 7.93 | 7.92 | 7.89 | 7.45 |
| Lignin (%) | 17.93 | 18.941 | 20.89 | 20.45 | 23.6 | 22.96 | 24.27 | 24.92 |
| Ash (%) | 30.92 | 14.04 | 5.8 | 4.23 | 2.06 | 4.09 | 3.98 | 4.27 |
| Extractive (%) | 2.49 | 2.019 | 1.71 | 1.41 | 1.35 | 1.48 | 1.21 | 0.85 |
| Moisture content (%) | 5.36 | 8.64 | 7.92 | 8.37 | 8.19 | 7.72 | 8.12 | 8.7 |

**Table 3**
Mechanical, physical and chemical properties of sugar palm fibre obtained from different parts (Sahari et al., 2012).

| Fibres | Sugar palm frond (SPF) | Sugar palm bunch (SPB) | Sugar palm trunk (SPT) | *Ijuk* |
|---|---|---|---|---|
| Tensile strength (MPa) | 421.4 | 365.1 | 198.3 | 276.6 |
| Tensile modulus (GPa) | 10.4 | 8.6 | 3.1 | 5.9 |
| Elongation at break (%) | 9.8 | 12.5 | 29.7 | 22.3 |
| Diameter (μm) | 115.4 | 254.7 | 596.2 | 221 |
| Holocellulose (%) | 81.2 | 71.8 | 61.1 | 65.6 |
| Cellulose (%) | 66.5 | 61.8 | 40.6 | 52.3 |
| Hemicelluloses (%) | 14.7 | 10 | 20.5 | 13.3 |
| Lignin (%) | 18.9 | 23.5 | 46.4 | 31.5 |
| Ash (%) | 3.1 | 3.4 | 2.4 | 4 |
| Extractive (%) | 2.5 | 2.2 | 6.3 | 4.4 |
| Moisture content (%) | 2.7 | 2.7 | 1.5 | 7.4 |

(Aidy, Sanuddin, & Ezzeddin, 2010; Bachtiar, Sapuan, & Hamdan, 2008c; Ishak, Leman, Sapuan, & Misri, 2009a; Ishak, 2009; Leman, Sastra, Sapuan, Hamdan, & Maleque, 2005; Leman, Sapuan, Saifol, Maleque, & Ahmad, 2008d; Leman, 2009; Misri, Leman, Sapuan, & Ishak, 2010a; Siregar, 2005; Suriani, Hamdan, Sastra, & Sapuan, 2006) have also been carried out.

Leman et al. (2005) studied the effect of fibre orientations (long and short fibres) on the impact strength of sugar palm fibre used to reinforce epoxy composites. The result showed that the impact strength of long fibre composites was higher compared to the impact strength of short fibre composite. The study also found that both long and short fibre composites have higher impact strength than pure epoxy matrix. This indicates that fibre absorbs energy and reduces crack propagation in brittle epoxy matrix.

A study by Siregar (2005) also looked at the effects of fibre orientations but with a slight difference in focus from that of Leman's et al. (2005). They studied the fibre orientation of woven, long and short random fibres and tested for tensile and flexural properties of sugar palm fibre used to reinforce epoxy composites. The results indicated that with the same fibre loading (10 wt%), the composite with orientation of woven fibre gave higher tensile and flexural properties than long fibre, while short random fibre composite had the lowest properties. This study was continued by Suriani et al. (2006) who investigated the correlation between the interfacial bonding with their fibre orientations (woven, long and short random fibres) at various fibre weight fractions (10, 15 and 20%). Fractured surface of the composites were analysed and evaluated in details using scanning electron microscope (SEM). It was observed that composites with orientation of long and short random fibre composites showed clear evidence of having poor interfacial bonding where more fibre pulled out especially for short random fibre composites, at all fibre weight fractions.

Based on good mechanical performance of woven sugar palm fibre composites obtained by previous research (Siregar, 2005), Ishak (2009) carried out a study on the effect of fibre content (wt%) on mechanical properties of woven sugar palm fibre composites at fibre weight fractions of 13% (1 layer), 18% (2 layers), 22% (3 layers) and 29% (4 layers) with the matrix being unsaturated polyester. In general, the results showed that tensile strength, tensile modulus, elongation at break, flexural strength and impact strength of the composites significantly increased (at $p \leq 0.05$) as the fibre content increased, while no significant increase was seen in flexural modulus. In general, it can be said that composites with higher fibre contents require higher force to break them after tensile and flexural tests. It was also observed that the addition of high amount of reinforcement fibres (29% (4 layers)) act to reduce the crack propagation in composite as well as increase the ability of the composite to resist fracture energy after impact test.

Leman (2009) carried out a series of mechanical tests namely tensile, flexural and impact tests on the composites with 10%, 15%, 20% and 30% (by volume) of randomly short chopped sugar palm fibres. The results showed that the strengths increased with the increase of fibre loadings of up to 20%, but the composite with 30% fibre content showed conflicting behaviour.

Further comparative study on tensile properties of single fibre obtained from different parts of sugar palm tree (*ijuk*, frond, trunk and bunch fibres) was continued by Sahari, Sapuan, Zainudin, and Maleque (2012a) where the properties were used to reinforce unsaturated polyester. It was found that sugar palm frond fibre used to reinforce unsaturated polyester composite (SPF/PE) had the highest tensile strength (15.18 MPa), followed by sugar palm bunch fibre (SPB/PE (12.81 MPa)), and by *ijuk* fibre (*ijuk*/PE (11.47 MPa) (Table 4)). The lowest tensile strength was found in sugar palm trunk fibre (SPT/PE (9.82 MPa)). For the results of tensile modulus, the sequence was as follows – for SPT/PE, *ijuk*/PE, SPB/PE and SPF/PE, their results were 555.71 MPa, 446.68 MPa, 426.45 MPa and 399.01 MPa, respectively, while for the elongation at break, the results were in reverse to tensile modulus (SPF/PE 8.07%, SPB/PE 5.04%, *ijuk*/PE 4.45% and SPT/PE 3.19%). For the impact strength, SPF/PE showed the highest value which was 8.09 kJ/m$^2$. The bending (flexural) properties of these composites were also studied by Sahari, Sapuan, Ismarrubie, and Rahman (2012b). The results showed that the highest bending strength and stiffness (modulus) were found at SPT/PE (41.91 MPa and 3.36 GPa, respectively), followed by SPF/PE (38.91 MPa and 3.00 GPa, respectively), SPB/PE (35.17 MPa and 2.75 GPa, respectively) and ijuk/PE (33.74 MPa and 2.42 GPa). Physical properties (water absorption and thickness swelling) of these composites were also studied (Sahari et al., 2011a). It was found that SPF/PE showed higher water absorption and thickness swelling (1.57% and 1.56%, respectively), followed by SPB/PE (1.35%, 1.11%), *ijuk*/PE (0.65%, 0.76%) and SPT/PE (0.39%, 0.50%).

**Table 4**
Mechanical and physical properties of unsaturated polyester composites reinforced sugar palm fibre obtained from different parts.

| Composites | SPF/PE | SPB/PE | SPT/PE | *Ijuk*/PE | Ref. |
|---|---|---|---|---|---|
| Tensile strength (MPa) | 15.18 | 12.81 | 9.82 | 11.47 | Sahari et al. (2011a) |
| Tensile modulus (GPa) | 0.39 | 0.43 | 0.56 | 0.47 | Sahari et al. (2011a) |
| Elongation at break (%) | 8.07 | 5.04 | 3.19 | 4.45 | Sahari et al. (2011a) |
| Flexural strength (MPa) | 38.91 | 35.17 | 41.90 | 33.74 | Sahari, Sapuan, Ismarrubie, Rahman (2011) |
| Flexural modulus (GPa) | 3.00 | 2.75 | 3.36 | 2.42 | Sahari, Sapuan, Ismarrubie, et al. (2011) |
| Impact strength (kJ/m$^3$) | 8.09 | 6.58 | 3.92 | 4.57 | Sahari et al. (2011a) |
| Water absorption (%) | 1.57 | 1.35 | 0.39 | 0.65 | Sahari et al. (2011c) |
| Thickness swelling (%) | 1.56 | 1.11 | 0.50 | 0.76 | Sahari et al. (2011c) |

Aidy et al. (2010) studied the effects of ageing on sugar palm fibre that is used to reinforce epoxy composites. The study was carried out to investigate how the ageing process of sugar palm fibre used in the composite reinforcement affects tensile and impact properties. Sugar palm fibres were aged at constant temperature of 70 °C for the duration of 70 h in an oven. This was done due to the fact that the accelerated ageing time is equivalent to 70 days ageing in a natural environment. The results showed the aged composites to have a tensile strength that was 50.4% higher than the non ageing composites, while the result of impact strength did not show any significant changes. Based on this result, it was proven that sugar palm fibre has high durability and can sustain its properties even after it is matured for 70 days in a natural environment.

The study also looked at the effect of water immersion on water absorption, dimensional stability and impact strength of sugar palm fibre used to reinforce unsaturated polyester composites (Umar, Leman, Zainudin, Sapuan, & Ishak, 2010). Water absorption of composites increased by 0.47% after being immersed in distilled water for 24 h indicates that the amount of water absorbed is due hygroscopic behaviour of natural fibre. No changes in tangential, radial or longitudinal to dimensional of composite were observed after specimens were immersed in distilled water. However, it is interesting to note that the impact strength of immersed composite specimen (2.31 kJ/m$^2$) was higher than the controlled specimens (1.74 kJ/m$^2$). This might be due to the fact that fibre responds well to water absorption. As water molecules enter fibre cell wall, they diffuse in cell wall and occupy the space in fibre lumen, causing the density of the fibre to increase. As a general rule, more energy is required to break the specimen. Hence, it increases the impact strength of the composite by 38%. This circumstance is similar to the theory applied in the densification of wood in order to enhance its mechanical properties as density is directly proportional to mechanical properties.

Leman, Sapuan, Saifol, et al. (2008) carried out a study on moisture absorption properties and equilibrium conditioning of sugar palm fibre used to reinforce epoxy composites. They looked at moisture absorption or desorption behaviour of sugar palm fibre composites through thickness and showed that water transported in sugar palm composite followed a typical dual sorption diffusion process and the diffusion process which is in accordance to Fick's law. The behaviour of the through thickness direction follows a parabolic behaviour. The value led to the determination of the Fickian diffusivity constant which showed that the 20% fibre composite plates have higher value of Fickian constant and are able to absorb more water compared to the 10% fibre composite plates.

Recent study by Ibrahim (2011) on the potential of natural fibre ash as filler for polymer composites indicated that ash from sugar palm fibre has slightly higher silica content (3.1%) than ash from oil palm fibre ash (2.96%). This was based on the result of X-ray diffraction (XRD). The higher silica content shows its potential to be used as filler in thermal insulator composites. However, in term of density, the results showed that sugar palm ash (SPA) has a higher density (1.52 g/cm$^3$) compared to oil palm ash (OPA) (1.28 g/cm$^3$).

## 5. Treatment of sugar palm fibre

In order to enhance interfacial properties of natural fibre composites, surface treatment on natural fibres is needed. Bachtiar (2008), Bachtiar, Sapuan, and Hamdan (2008b), Bachtiar et al. (2008c), Bachtiar, Sapuan, and Hamdan (2009a) studied the effects of alkaline treatment of sugar palm fibre by sodium hydroxide (NaOH) on mechanical properties of sugar palm fibre used to reinforce epoxy composites. The results (Table 5) verified that mechanical properties (tensile, flexural and impact) of the composites increased particularly for tensile modulus. This is due to the reduction of hydrophilic property of sugar palm fibre after the treatment which had increased the interfacial bonding between sugar palm fibre and epoxy matrix. This is achieved after treating the fibre with NaOH to react with hydrophilic hydroxyl groups of the fibre and improves hydrophobic characteristics and facilitates good interfacial bonding with matrix materials. Apart from that, the same study reported that higher concentration of alkaline solution and prolonged soaking time resulted in the decrease in mechanical properties of the composites. Even though the surface of sugar palm fibre had been treated, the over treated samples led to the weakening of the fibre cell wall, resulting in inferior fibre mechanical properties. This shows that when stress is transferred to the fibre, the fibre breaks.

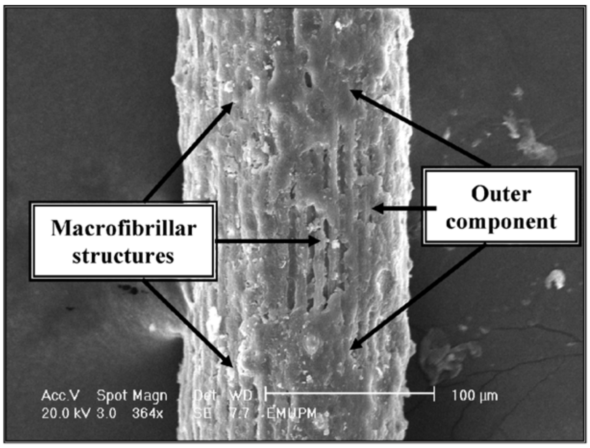
A study conducted by Leman, Sapuan, Azwan, Ahmad, and Maleque (2008), Leman, Sapuan, and Ahmad (2008c), Leman, Sapuan, Ishak, and Ahmad (2010) stressed that the mechanical properties of sugar palm fibre used to reinforce epoxy composites could also be increased by using sea water treatment. The process includes soaking sugar palm fibre for 30 days. Fig. 2a reveals the morphological surface of sugar palm fibres after soaking in sea water for 30 days. Based on the observation on its microstructure, there is strong evidence that the sea water treatment changed the physical surface appearance of sugar palm fibre compared to untreated sugar palm fibre (Fig. 2b). It shows that a drastic physical changes with slight fibrillation are clearly observed on the outer surface of the fibre where the outer surface became clear and this is due to the removal of the waxy layer on the outer surface (Fig. 3).

This is the reason behind using sea water as treatment agent; besides of its abundantly availability at low cost, the chemistry behaviour of its salty water that would removes the undesirable components which covers the external surface of the fibre. In sea water, bacterial degradation on the fibre surface occurs in water through the micro organisms that can degrade fibre surface. The removal of these components are similar to the alkali treatment method that led to fibre fibrillation i.e. breaking down of fibre bundles into smaller fibres which increases the effective surface area available for contact with the matrix (Bledzki & Gassan, 1999). This results in the tensile and flexural properties of chopped sugar palm fibre used to reinforce epoxy composites increased tremendously after sea water treatment. This is thought to be because the sea water treated sugar palm fibres have good interfacial bonding with the matrix and resulting in their mechanical interlocking force between the fibre and the matrix became larger. The results showed

**Table 5**
Tensile properties of alkali treated sugar palm fibre reinforced epoxy composites.

| Concentration | Untreated | 0.25 M | | | 0.5 M | | | Ref. |
|---|---|---|---|---|---|---|---|---|
| Time of soaking (h) | | 1 | 4 | 8 | 1 | 4 | 8 | |
| Tensile strength (MPa) | 42.85 | 49.88 | 37.89 | 41.41 | 30.64 | 37.56 | 41.86 | Bachtiar et al. (2008c) |
| Tensile modulus (GPa) | 3.33 | 3.78 | 3.87 | 3.75 | 3.66 | 3.85 | 3.77 | Bachtiar et al. (2008c) |
| Elongation at break (%) | 1.32 | 1.32 | 1.00 | 1.17 | 0.8 | 1.01 | 1.11 | Bachtiar et al. (2008c) |
| Flexural strength (MPa) | 77.73 | 96.69 | 64.42 | 72.63 | 85.30 | 58.17 | 90.68 | Bachtiar (2008) |
| Flexural modulus (GPa) | 2.81 | 3.51 | 2.21 | 2.55 | 5.03 | 6.95 | 4.67 | Bachtiar (2008) |
| Impact strength (J/m) | 46.72 | 35.2 | 37.8 | 50.02 | 40.74 | 49.28 | 60.08 | Bachtiar et al. (2009a) |

a




b

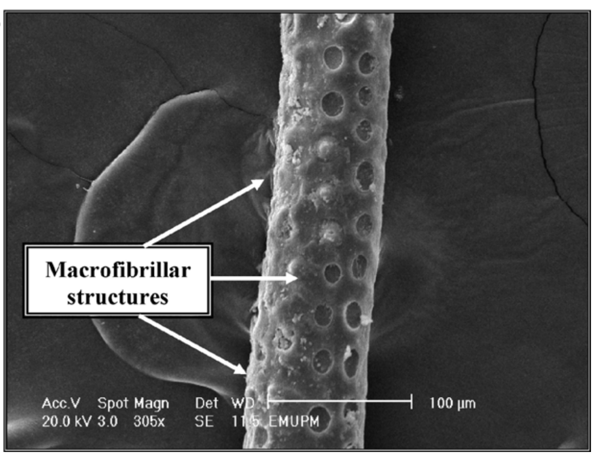



**Fig. 2.** Surface morphology of sea water treated (a) and untreated (b) sugar palm fibre (Ishak, 2009).

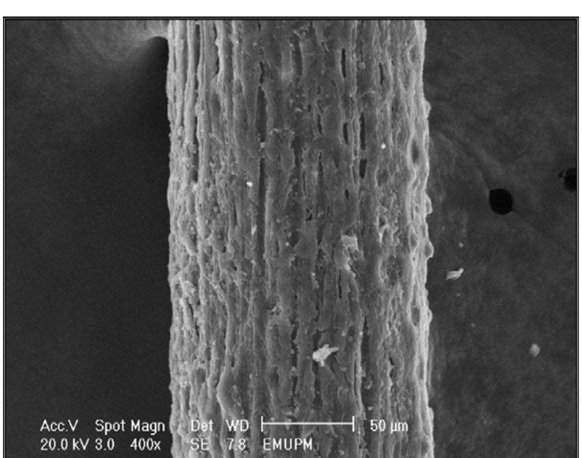



**Fig. 3.** Surface morphology of untreated sugar palm fibre (Ishak, 2009).

that the composite treated with sea water has better mechanical properties, followed by treated pond water, sewage water and finally untreated fibre composite. Similar finding was also reported by Ishak et al. (2009c). Recently, Leman, Sapuan, and Suppiah (2011) studied single fibre pull out test of sugar palm fibre which was embedded in unsaturated polyester after being treated with the same treatment method (sea water, pond water and sewage water for a period of 30 days) in order to study its fibre-matrix interfacial adhesion. The results in this study differed slightly with Leman, Sapuan, Azwan, et al. (2008), Leman, Sapuan, and Ahmad (2008) and Leman et al. (2010) as he found that freshwater-treated fibres possessed the highest interfacial shear strength, followed by untreated fibres, sewage water-treated fibres and lastly, sea water-treated fibres.

Ishak (2009), Ishak, Leman, Sapuan, Salleh, and Misri (2008) and Ishak, Leman, Sapuan, and Misri (2009b) also looked into the potential of sea water treatment for surface modification of woven sugar palm fibre used to reinforce unsaturated polyester composites. It was interesting to note that the opposite result was obtained by Leman, Sapuan, Azwan, et al. (2008), Leman et al. (2008c, 2010) in which sea water treatment resulted in composites with significant decrease in tensile strength, tensile modulus, elongation at break, flexural modulus and impact strength, with the exception of flexural strength. This could be due to the damage of fibre's cell wall structure as well as micro pores on fibre surface after being soaked in sea water for 30 days. Sugar palm fibres have micro pores on their surfaces (Fig. 3) which allow the matrix to fill into the holes to form good mechanical interlocking on their surfaces.

Other related studies on mechanical properties of sugar palm fibre used to reinforce polymer composites can be found in references (Bachtiar & Sapuan, 2010; Bachtiar, Sapuan, & Hamdan, 2008a; Bachtiar et al., 2008b, 2009a; Bachtiar, Sapuan, Khalina, & Dahlan, 2009b, 2009c; Bachtiar, Sapuan, Zainudin, & Dahlan, 2010; Bachtiar, Sapuan, Khalina, & Dahlan, 2010; Bachtiar, Sapuan, Khalina, Zainudin, & Zaman, 2010; Bachtiar, Sapuan, Zainudin, Khalina, & Dahlan, 2011a; Bachtiar, Sapuan, Zainudin, Khalina, & Dahlan, 2011b; Ishak, Sapuan, Leman, Sahari, & Ibrahim, 2010b; Leman, Sapuan, Salleh, Ishak, & Misri, 2008; Sahari, Sapuan, Rahman, Ishak, & Ibrahim, 2010; Sahari, Sapuan, Ismarrubie, et al., 2010; Sahari, Sapuan, Rahman, Ishak, & Ibrahim, 2010a; Sahari, Sapuan, Rahman, Ishak, & Ibrahim, 2010b; Sastra, Siregar, Sapuan, Leman, & Hamdan, 2005; Sastra, Siregar, Sapuan, Leman, & Hamdan, 2006; Suriani, 2006).

## 6. Properties enhancement of sugar palm fibre composites

In designing natural fibre composite products, it would be a mistake to assume that the properties of composite materials would remain unchanged. As a general rule, the mechanical properties of fibre composite such as the strength or stiffness of the composites after the ageing process are lower than those of the unexposed composites, and decrease as the ageing time increases. The ambient moisture content, chemicals and radiation often cause a slow drift in physical and mechanical properties of fibre and composite (Abral, Andriyanto, Samera, Sapuan, & Ishak, 2012; Abral, Gafar, et al., 2012; Gouanvé, Marais, Bessadok, Langevin, & Métayer, 2007; Khalil, Ismail, Rozman, & Ahmad, 2001; Joseph et al., 1996; Pritchard, 2000; Ramgopal, Ramani, Ramachandra, & Ranganathaiah, 1998; Rozman et al., 2001; Subramanian, Senthil Kumar, Jeyapal, & Venkatesh, 2005; Xu, Ke, Wu, & Wang, 2006), giving the typical consequences of fibre and matrix swelling, fibre-resin debonding and matrix microcracking. This is due to the fact that natural fibre is of a hygroscopic material and its cell wall contains hydroxyl (OH) that absorbs moisture from the surrounding atmosphere until it reaches its equilibrium. However, it will release moisture when the equilibrium moisture content of the surrounding atmosphere is lower than the moisture content of the fibre. The moisture absorption and desorption occur mainly through the cell wall of fibre. This is the main problem of all natural fibre composite products in which the shrinking or swelling of the composites decreases the mechanical performance. The problem can be solved by altering the fibre through modification process. Preliminary fibre modification through fibre-resin impregnation was proposed by Ishak, Sapuan, Leman, Sahari, and Ibrahim (2010c) in his preliminary study before it is being used as composite reinforcement. The idea is to impregnate all the empty spaces of sugar palm fibre (lumen cavity and cell wall) with polymer resin.

The effects of impregnation modification via vacuum resin impregnation on physical and mechanical properties of sugar palm fibres were investigated (Table 6) (Ishak, Leman, Sapuan, Rahman, & Anwar, 2011a). The fibre was evacuated at a constant impregnation pressure of 1000 mmHg impregnation times (0, 5, 10, 15, 20 and 25 min) with two different impregnation agents:phenol formaldehyde (PF) and unsaturated polyester (UP). A notable improvement in the physical properties of sugar palm fibres was observed after they were impregnated with PF and UP for 5 min, shown by the reduction of their moisture content (MC) (91% and 89%, respectively) and water absorption (WA) (43% and 41%, respectively) compared to the control sample. However, no significant improvement ($p \leq 0.05$) in the physical properties of fibre was observed when the impregnation time was extended (from 10 to 25 min) using both impregnation agents. The lower MC and WA of impregnated fibres could be explained as the fibre had been impregnated, the resin effectively served as a barrier from diffusion of water molecules into cell wall and cell lumen or at least it reduced permeability behaviour of the fibre once the micropores were blocked with the resin.

In term of mechanical properties of the impregnated fibre, significant improvement was observed after they were impregnated for 5 min. The fibres impregnated with UP resulted in better fibre toughness and improved mechanical properties as shown in their higher tensile strength and elongation at break compared to the fibres impregnated with PF (Table 6). Both the physical and mechanical properties showed no significant improvement ($p \leq 0.05$) after time for impregnation was extended (from 10 to 25 min) using both impregnation agents. Therefore, it can be concluded that the physical and mechanical properties of sugar palm fibre could be enhanced by impregnating the fibre with thermosetting polymer (PF and UP) for 5 min. It was shown that impregnation with UP showed better improvement than PF. In addition, this study also concluded that the unsatisfactory enhancement of the properties of sugar palm fibre even after the impregnation time was extended from 10 to 25 min was due to the use of low impregnation pressure of 1000 mmHg.

Since pressure is one of the main factors that aids penetration of impregnation agent into cell wall and lumen of natural fibres, the investigation on the effects of elevating impregnation pressure (1000, 900, 800, 700, 600 and 500 mmHg) on physical and mechanical properties of sugar palm fibre with PF and UP at constant impregnation time of 5 min was further carried out by Ishak, Leman, Sapuan, Rahman, and Anwar (2011b). Significant increase in the WPG of sugar palm fibres was observed after impregnating them with pressure with PF and UP in the ranges of 8.59–38.59% and 7.16–22.63%, respectively (Table 7). In addition, it was observed that PF-impregnated fibres had their specific gravity increased from 1.22 to 1.29 and 1.33 after being impregnated with pressures of 600 and 500 mmHg. However, no significant increase was observed in specific gravity for fibres impregnated with unsaturated polyester. As for the physical properties of the impregnated fibres, it was shown that there was a significant improvement ($p \leq 0.05$) in the properties when the impregnation pressure was gradually increased. Additional findings showed that the fibre moisture content dropped from 8.19% to 0.75–0.46% for PF and 0.87–0.44% for UP, while water absorption was reduced from 116.82% to 61.64–22.52% for PF and 63.49–23.31% for UP. There was not much difference in the reduction of fibre moisture content and water absorption between the two impregnation agents (PF and UP). The mechanical properties of impregnated fibres showed significant improvement ($p \leq 0.05$) with the increase of pressure. The tensile strength increased from 243.77 MPa to 251.39–297.67 MPa for PF and 287.84–344.71 MPa for UP. The tensile modulus increased from 3.07 GPa to 3.1–3.98 GPa for PF and 3.15–3.98 GPa for UP, while the elongation at break decreased from 25.16% to 17.66–6.26% for PF and 24.24–19.05% for UP. Low tensile strength and elongation at break of PF-impregnated fibres showed that their fibres are inferior in toughness (48.51 MJ/m$^3$ to 33.08–12.29 MJ/m$^3$) compared to UP-impregnated fibres (48.51 MJ/m$^3$ to 57.56–45.21 MJ/m$^3$).

The effect of this fibre modification on physical properties of sugar palm fibre reinforced unsaturated polyester composites was also studied by Ishak, Sapuan, Leman, Rahman, Anwar, and Chua (2011). The fibres were impregnated with unsaturated polyester at the pressure of 600 mmHg (79.99 kPa) for 5 min before they were used to reinforce unsaturated polyester composites at 10, 20, 30, 40 and 50% fibre loadings. After bulking the OH groups of sugar palm fibre's cell wall, it was observed that MC and WA of impregnated sugar palm fibre composites were significantly lower than of the control samples (unmodifed fibre composites). It was also observed that the impregnated fibre composites exhibited better moisture repellence with the increase of impregnated fibre loading as indicated by the increase of moisture excluding efficiency (MEE). Beside the reduction of moisture and water uptakes, the reduction of the size of microfibril was also observed. This caused the impregnated composites to have lower thickness swelling (TS) and linear expansion (LE) than control samples. It was also established that the dimensional stability of the composites increased with the increase in impregnated fibre loading.

For the effect to mechanical properties of the composites, the composites of 10, 20, 30, 40 and 50% fibre loadings of impregnated fibre and control were tested for tensile, flexural and impact properties (Ishak, Sapuan, Leman, Rahman, Anwar, & Chin, 2011). It was observed that impregnation resulted in significant physical changes in sugar palm fibre surface where the surface was enclosed by UP. This has found to have a strong influence on the interfacial bonding of the fibre and matrix in the composites. For this reason, composite with UP-impregnated fibre had consistently higher flexural and impact properties than the control samples. It was also observed that the best fibre loading to yield the maximum flexural and impact properties of composites was found to be at 30% beyond which a decreasing trend was obtained.

## 7. Developments of biopolymer from sugar palm

It is well known fact that the development of biopolymers would produce environmental friendly materials as alternatives to synthetic polymers for many applications. This leads this issue to

**Table 6**
WPG, SG, MC, WA, tensile properties and toughness of impregnated sugar palm fibre PF and UP at various impregnation times.

| Time, *T* (min) | | Control | 5 | 10 | 15 | 20 | 25 | Ref. |
|---|---|---|---|---|---|---|---|---|
| Weight percentage gain, WPG (%) | PF | – | 9.45 a (1.08) | 9.79 a (1.25) | 8.24 a (1.51) | 8.66 a (0.88) | 9.92 a (1.14) | Ishak, Leman, Sapuan, Rahman, and Anwar (2012) |
| | UP | – | 6.35 a (1.15) | 7.96 a (0.82) | 6.73 a (1.53) | 7.51 a (0.87) | 8.4 a (1.43) | |
| Specific gravity, SG | PF | 1.23 a (0.02) | 1.24 a (0.03) | 1.23 a (0.04) | 1.24 a (0.03) | 1.23 a (0.03) | 1.26 a (0.03) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011a) |
| | UP | 1.23 a (0.02) | 1.19 a (0.08) | 1.22 a (0.05) | 1.24 a (0.06) | 1.24 a (0.06) | 1.27 a (0.05) | |
| Moisture content, MC (%) | PF | 8.17 a (0.47) | 0.71 b (0.19) | 0.73 b (0.47) | 0.73 b (0.33) | 0.70 b (0.43) | 0.71 b (0.30) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011a) |
| | UP | 8.17 a (0.47) | 0.83 b (0.14) | 0.92 b (0.35) | 0.79 b (0.48) | 0.97 b (0.31) | 0.89 b (0.30) | |
| Water absorption, WA (%) | PF | 111.40 a (7.12) | 62.63 b (3.48) | 62.50 b (7.15) | 66.18 b (5.19) | 63.85 b (4.89) | 64.12 b (4.00) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011a) |
| | UP | 111.40 a (7.12) | 67.02 b (2.77) | 68.37 b (2.51) | 64.76 b (5.38) | 67.22 b (4.96) | 63.35 b (5.07) | |
| Tensile strength (MPa) | PF | 241.93 a (2.47) | 254.85 b (4.99) | 256.30 b (6.50) | 248.51 b (7.07) | 254.67 b (6.38) | 257.14 b (6.02) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011a) |
| | UP | 241.93 a (2.47) | 283.75 b (6.21) | 280.98 b (5.35) | 285.06 b (6.07) | 288.17 b (6.61) | 290.36 b (5.29) | |
| Tensile modulus (GPa) | PF | 3.07 a (0.01) | 3.13 b (0.01) | 3.17 c (0.01) | 3.17 c (0.01) | 3.18 c (0.01) | 3.17 c (0.01) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011a) |
| | UP | 3.07 a (0.01) | 3.11 b (0.01) | 3.12 b (0.01) | 3.13 b (0.01) | 3.11 b (0.01) | 3.11 b (0.01) | |
| Elongation at break (%) | PF | 25.16 a (0.31) | 19.37 b (4.05) | 17.29 b (2.19) | 18.71 b (3.35) | 15.44 b (4.21) | 16.25 b (3.53) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011a) |
| | UP | 25.16 a (0.31) | 23.09 b (1.62) | 22.21 b (1.12) | 20.62 b (3.19) | 21.82 b (2.22) | 21.67 b (2.37) | |
| Toughness (MJ/m$^3$) | PF | 48.53 a (5.23) | 34.01 b (3.51) | 39.10 b (3.53) | 34.34 b (3.04) | 27.17 c (2.49) | 28.52 c (1.25) | Ishak (2012) |
| | UP | 48.53 a (5.07) | 48.50 a (5.72) | 42.89 a (3.82) | 42.16 a (3.35) | 45.70 a (4.45) | 46.26 a (2.39) | |

*Note*: Mean followed with the same letters $^{a,b,c}$ in row were not significantly different ($p \leq 0.05$), values in parentheses are standard error.

**Table 7**
WPG, SG, MC, WA, tensile properties and toughness of impregnated sugar palm fibre PF and UP at various impregnation pressure (Ishak, Leman, Sapuan, Rahman, & Anwar, 2011b).

| Time, *T* (min) | | Control | 1000 | 900 | 800 | 700 | 600 | 500 | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| Weight percentage gain, WPG (%) | PF | – | 8.59 a (1.38) | 12.05 b (1.25) | 19.53 c (1.06) | 25.05 d (2.38) | 34.42 e (1.27)) | 38.59 f (2.27) | Ishak (2012) |
| | UP | – | 7.16 a (1.31) | 11.57 b (1.16) | 14.58 c (1.62) | 16.47 c (2.21) | 21.89 d (1.41) | 22.63 d (2.27) | |
| Specific gravity, SG | PF | 1.22 a (0.02) | 1.22 a (0.01) | 1.24 a (0.01) | 1.25 a (0.01) | 1.27 a (0.03) | 1.29 b (0.02) | 1.33 c (0.03) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011b) |
| | UP | 1.22 a (0.02) | 1.22 a (0.01) | 1.23 a (0.01) | 1.24 a (0.02) | 1.25 a (0.02) | 1.25 a (0.01) | 1.26 a (0.01) | |
| Moisture content, MC (%) | PF | 8.19 a (0.08) | 0.75 b (0.02) | 0.63 c (0.01) | 0.46 d (0.09) | 0.41 d (0.12) | 0.42 d (0.05) | 0.46 d (0.09) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011b) |
| | UP | 8.19 a (0.08) | 0.87 b (0.03) | 0.79 c (0.01) | 0.44 d (0.02) | 0.48 d (0.04) | 0.53 d (0.04) | 0.49 d (0.04) | |
| Water absorption, WA (%) | PF | 116.82 a (6.39) | 61.64 b (2.12) | 42.84 c (4.09) | 30.49 d (0.46) | 26.03 e (0.64) | 24.32 f (0.02) | 22.52 g (0.15) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011b) |
| | UP | 116.82 a (6.39) | 63.49 b (2.09) | 46.55 c (2.30) | 33.01 d (0.55) | 26.61 e (0.23) | 23.97 f (0.51) | 23.31 f (0.03) | |
| Tensile strength (MPa) | PF | 243.77 a (1.46) | 251.39 b (3.43) | 263.36 c (4.15) | 271.44 d (3.59) | 279.88 e (2.70) | 288.41 f (4.55) | 297.67 g (5.43) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011b) |
| | UP | 243.77 a (1.46) | 287.84 b (3.99) | 304.59c (2.32) | 312.99 d (4.52) | 326.07 e (3.35) | 341.60 f (4.33) | 344.71 f (3.68) | |
| Tensile modulus (GPa) | PF | 3.07 a (0.22) | 3.15 b (0.16) | 3.39 c (0.04) | 3.55 d (0.05) | 3.73 e (0.00) | 3.89 f (0.03) | 3.98 f (0.06) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011b) |
| | UP | 3.07 a (0.22) | 3.10 b (0.08) | 3.27 c (0.03) | 3.41 d (0.03) | 3.51 e (0.01) | 3.59 f (0.01) | 3.60 f (0.01) | |
| Elongation at break (%) | PF | 25.16 a (0.34) | 17.66 b (0.23) | 15.50 c (0.42) | 12.88 d (0.44) | 10.595 e (0.40) | 8.60 f (0.47) | 6.26 g (0.20) | Ishak, Leman, Sapuan, Rahman, and Anwar (2011b) |
| | UP | 25.16 a (0.34) | 24.24 b (0.16) | 22.945 c (0.29) | 21.455 d (0.17) | 20.95 e (0.19) | 19.17 f (0.21) | 19.05 f (0.15) | |
| Toughness (MJ/m$^3$) | PF | 48.51 (5.51) | 33.08 (6.58) | 26.46 (1.55) | 21.71 (1.88) | 17.81 (2.37) | 12.98 (1.25) | 12.29 (2.05) | Ishak (2012) |
| | UP | 48.51 (5.52) | 57.56 (7.84) | 50.75 (3.56) | 47.68 (3.14) | 48.05 (3.33) | 45.12 (5.25) | 45.21 (5.15) | |

*Note*: Mean followed with the same letters $^{a,\ b,\ c}$ in row were not significantly different ($p \leq 0.05$), values in parentheses are standard error.

**Table 8**
Composition of typical starches.

| Starch | Amylose (%) | Amylopectin (%) | Protein (%) | Moisture (%) | Ref. |
|---|---|---|---|---|---|
| Wheat | 26–27 | 72–73 | 0.30 | 13 | Avérous and Halley (2009) |
| Maize | 26–28 | 71–73 | 0.30 | 12–13 | Avérous and Halley (2009) |
| Waxi starch | <1 | 99 | 0.10 | n.d. | Avérous and Halley (2009) |
| Amylomaize | 50–80 | 20–50 | 0.50 | n.d. | Avérous and Halley (2009) |
| Potato | 20–25 | 79–74 | 0.05 | 18–19 | Avérous and Halley (2009) |
| Sago[a] | | | | | |
| Plawei | 22.4 | 77.1 | – | – | Tie, Karim, and Manan (2008) |
| Bubul | 22.7 | 77.3 | – | – | Tie et al. (2008) |
| Angau Muda | 24.2 | 75.88 | – | – | Tie et al. (2008) |
| Angau Tua | 25.4 | 74.6 | – | – | Tie et al. (2008) |
| Late Angau Tua | 26.0 | 74.0 | – | – | Tie et al. (2008) |

[a] Obtained at mid height.


**Fig. 4.** Sugar palm trunk (Sahari & Sapuan, 2011b).

become an attractive study to be carried out among materials scientists in recent years (Chen, Cao, Chang, & Huneault, 2008; De Carvalho, Curvelo, & Agnelli, 2001; Follain, Joly, Dole, & Bliard, 2005; Forssell, Mikkia, Moates, & Parker, 1997; Ibrahim, El-Zawawy, & Nassar, 2010; Khan, Bhattacharia, Kader, & Bahari, 2006; Lawton and Fanta, 1994; Shi et al., 2008; Sin, Rahman, Rahmat, Sun, & Samad, 2010; Tang, Alavi, & Herald, 2008; Tang, Zou, Xiong, & Tang, 2008; Wilhelm, Sierakowski, Souza, & Wypych, 2003; Zhai, Yoshii, Kume, & Hashim, 2002; Zhai, Yoshii, & Kume, 2003).

Another potential product from sugar palm is biopolymer. Since sugar palm produces starch from its trunk, the starch can be used to make biodegradable polymer. The existence of the starch is proven by many researchers (Dransfield & Uhl, 1986; Hyene, 1950; Ishak et al., 2010b, 2010c; Ishak, 2009; Miller, 1964; Mogea et al., 1991; Mogea, 1991; Moore, 1960; Redhead, 1989; Sahari & Sapuan, 2011a) and also proven by the fact that sugar palm starch has been used traditionally by the locals to make flour, noodles, *'mee hoon'* and animal feeds until now. According to Muhtadi (1991), one sugar palm tree can produce 50–100 kg of starch.

The starch content of sugar palm is currently being studied, however, the starch contents from other commonly used starches are shown in Table 8 for review purpose.

We have recently derived the starch in order to study the characterisation of this new biopolymer and currently is being studied actively by Sahari, Sapuan, Zainudin, and Maleque (2011b) and Sahari et al. (2011a) on effects of plasticizers on physical and mechanical properties of sugar palm starch. This study is intended to develop a new biodegradable biopolymer derived from sugar palm, as shown in Fig. 4.

The polymer was derived from sugar palm starch (SPS) in the presence of biodegradable glycerol as plasticizer. A series of environmentally friendly plasticized SPS were successfully prepared using 15–40% (w/w) of unmodified glycerol as plasticizer. It was observed that the physical properties such as density, moisture content, water absorption and thickness swelling of the plasticized SPS had lower with the increase of glycerol.

**Fig. 5.** Sugar palm fibre composite boat (Ishak, Sapuan, Leman, Sahari, & Ibrahim, 2010b).

Other studies using SPS in producing biopolymer was reported in Poeloengasih, Zahra, and Widyasari (2011)'s studies. They used SPS and combined with chitosan to produce edible film materials. Plasticizer such as glycerol and sorbitol were added to produce strong and flexible film. The composite films were prepared from chitosan and SPS in various ratios with glycerol and sorbitol. The films of chitosan:SPS (0:100; 25:75; 50:50; 75:25, and 100:0) with 30 (w/w) concentration of plasticizer were produced and the properties of the films, i.e. thickness, solubility in water, water vapour transmission rate, tensile strength and elongation of films were characterised. The result showed that variations of chitosan:SPS ratio influenced the characteristic of the films. Thickness of chitosan:SPS film with glycerol and sorbitol as plasticizer was in ranged between 0.091–0.113 mm and 0.084–0.113 mm, respectively. For film with glycerol as plasticizer, the highest solubility in water was 42.97 obtained from film with chitosan:SPS ratio of 75:25, whereas the lowest water vapour transmission rate was 12.87 g/h m$^2$ obtained from 100:0 SPS film. The lowest tensile strength and the highest elongation were 4.20 MPa and 50.47%, respectively obtained from film with a chitosan:SPS ratio of 75:25. For film with sorbitol as plasticizer, the highest solubility in water was 49.41% obtained from film with a chitosan:SPS ratio of 75:25, whereas the lowest water vapour transmission rate was 7.39 g/h m$^2$ obtained from film with 100% SPS. The lowest tensile strength and the highest elongation, i.e. 5.38 MPa and 22.59% respectively, were results from film with a chitosan:SPS ratio of 50:50.

## 8. Developments of composite products

Several products have been successfully developed from sugar palm fibre composites. For example, Misri, Leman, Sapuan, Salleh, and Ishak (2008), Misri et al. (2010a) and Misri, Leman, Sapuan, and Ishak (2010b) presented the fabrication of a hybrid unsaturated polyester composite boat made from sugar palm and glass fibres, shown in Fig. 5. The boat which is up to 12 feet in length was fabricated using the combination of compression moulding and hand lay-up technique. The boat was made of 2 layers of fibres (woven sugar palm and glass fibres) with unsaturated polyester as matrix. The development of the boat has successfully reduced the use of glass fibre by up to 50%. The weight of the boat has also been reduced since the density of sugar palm is as low as 1.22–1.26 kg/m$^3$ (Ishak, Sapuan, Leman, Rahman, & Anwar, 2011; Ishak, Leman, Sapuan, Rahman, & Anwar, 2011a; Ishak, Leman, Sapuan, Rahman, & Anwar, 2011b) compared to the commercialised E-glass fibre which has the density of 2.55 kg/m$^3$ (Bismarck, Mishra, & Lampke, 2005). Other products that have been developed using sugar palm fibre to reinforce epoxy composites are safety helmet and portable table. The helmet is named Helmet-Ijuk Reinforced Composite (H-IReC), designed to absorb and withstand high impact and is water resistant. The portable table which is also designed and fabricated from sugar palm fibre has fancy top surfaces, is multipurpose and can be used as a work bench (Mujahid, 2009).

## 9. Conclusions

Sugar palm fibre with its desirable properties, has great potential to be used as reinforcement in polymer composites. Not only the fibre is highly durable, it is also resistant to sea water. On top of it, it is readily available in the form of woven fibres, making it easy to process. Currently, several successful sugar palm fibre composite products are being developed. Since sugar palm remains largely unknown by many people and very little information is available about it, more research needs to be conducted to unveil its significance and to promote its usefulness for the benefits of the public.

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