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Sugar Palm Fibre and its Composites: A Review of Recent Developments

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The use of natural fibres as reinforcement in composite materials has increased over the years due to the rapid demand for renewable, cost-effective, and eco-friendly materials in many applications. The most common and adopted natural fibres used as reinforcements are flax, kenaf, hemp, jute, coir, sisal, and abaca. However, sugar palm fibre (SPF) as one of the natural fibres is gaining acceptance as a reinforcement in composites, though it has been known for decades in the rural communities for its multipurpose traditional uses. Sugar palm fibre (SPF) is extracted from sugar palm tree typically from its four morphological parts, namely, trunk, bunch, frond, and the surface of the trunk, which is known as *Ijuk*. In this paper, sugar palm tree, its fibre and composites, and biopolymers derived from its starch are discussed. Major challenges and the way forward for the use of sugar palm fibre and its composites are highlighted. This review also opens areas for further research on sugar palm fibre and its composites for academia and industries.

Keywords: Sugar palm fibre; Natural fibre composites; Biopolymer; Properties; Biodegradability

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INTRODUCTION

The increase in stringent regulations on carbon emissions, environmental concerns such as climate change, and the disposal of components at the end of their useful life has stimulated the use of environmentally friendly materials. In recent years, the furniture, automobile, packaging, aerospace, building, and construction industries have searched for new materials to replace the conventional glass fibre and other synthetic fibre composites. The most promising and adopted materials are natural fibre composites. Natural fibre composites are developed by a combination of two or more distinct materials to obtain a material with required properties and performance that is not obtainable from any distinct material (Bledzki and Gassan 1999). In a natural fibre composite, one material will be a matrix, while the other material will be a reinforcement produced from plants or animals, including bast, leaf, seed, fruit, stalk, grass, and wood. The matrix can either be thermoplastic, thermoset, or biopolymer. The most commonly used thermoplastic materials for natural fibre composites are polypropylene, polyethene, and poly (vinyl chloride) PVC; in thermoset plastics, they are epoxy, polyester, and phenolic (Malkapuram *et al.* 2008).

Natural fibre composites offer numerous advantages compared with glass fibre composites, including their light weight, biodegradability, ease of machinability, lack of toxicity, low cost, non-abrasive nature, and availability (Garkhail *et al.* 2000; Malkapuram *et al.* 2008). There are many natural fibre composites that are acceptable and well established through research. Wambua *et al.* (2003) investigated the mechanical properties of sisal, hemp, coir, kenaf, and jute reinforced polypropylene, and another study by Rao and Rao (2007) investigated the physical and mechanical properties of vakka, date, and bamboo. More recently, sugar palm fibre has been explored as a potential reinforcement in a polymeric matrix (Leman *et al.* 2005; Ishak *et al.* 2009; Sapuan *et al.* 2010; Ishak *et al.* 2012). With the evolution of these new natural fibre composites, certain precautions need to be taken with regard to the area of application. These composites should be critically evaluated and characterized for proper utilisation in a wider range of applications.

This review provides an overview of the sugar palm tree and its fibre and composites. The article highlights the characterization of sugar palm fibre, its chemical composition, treatment, and product development, as well as the engineering properties of sugar palm fibre reinforced thermoset, thermoplastic, and biopolymer composites. It will also open areas of further research of sugar palm fibre and its composites.

NATURAL FIBRES

Lignocellulose fibres or natural fibres are natural substances produced by plants (cellulose or lignocellulose), animals (protein), and minerals.

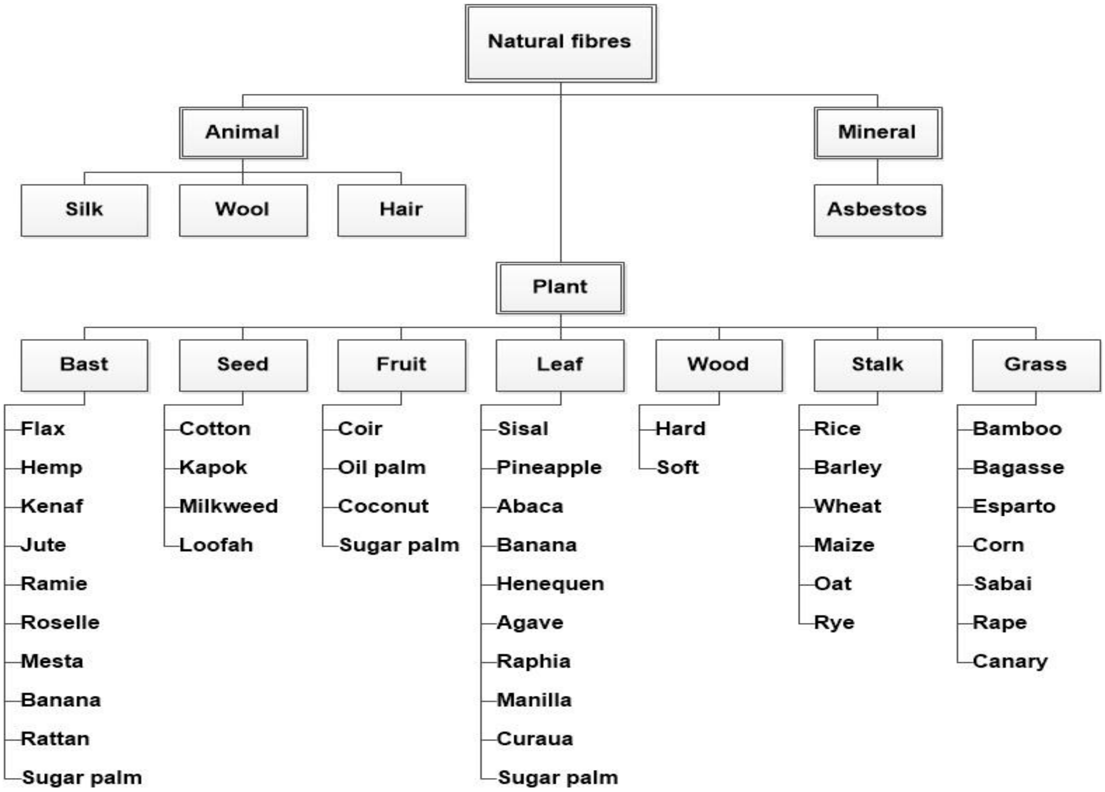

Fig. 1. Classification of natural fibres (redrawn from Jawaid and Khalil (2011) and Sanyang *et al*. (2016b))

Usually, these fibres are spun into filament, thread, or rope, and they can be matted, knitted, or woven as products or as a material for reinforcement. Natural fibres are found in many sources; the subdivision is based on their origins, coming from either plant, animal, or mineral as shown in Fig. 1 (Holbery and Houston 2006; Jawaid and Khalil 2011; Sanyang *et al.* 2016b). The bulk of natural fibres originate from plants including abaca, coir, cotton, flax, hemp, jute, ramie, and sisal; these are the most established natural fibres (Bledzki and Gassan 1999). The word “fibre” in this context refers to a structure that consist of several cells. These cells are organised and bonded together through mechanical interactions, hydrogen bonds, and van der Waals forces between domains of microfibrils of cellulose, hemicellulose, and lignin. (Pérez *et al.* 2002). The natural fibres are mostly in the form of agricultural waste that is unutilized, except for burning as fuel, thereby contributing to environmental problems. An assessment of biofuel use and agricultural waste field burning by Yevich and Logan (2003) showed that agricultural waste provides about 33% of the biofuel used globally. This agricultural waste is produced in billions of tonnes, which are in abundant and at low cost. Most of this waste could be used as fibres and fillers in polymeric composites. Because there are many sources of natural fibres, their utilisation in various industrial applications is undoubtedly supported by their bulk availability in many countries.

Based on the classification of natural fibres, sugar palm fibre being relatively new when compared with other natural fibres, it can find its position in more than one places. The reason is that the fibre from the sugar palm tree can come from either bunch, frond or trunk (Sahari *et al.* 2011, 2012; Ishak *et al.* 2013;). Therefore, sugar palm fibre can appear both under fruit, bast and leaf in the classification of natural fibres as shown in Fig. 1.

Natural fibres offer some advantages over synthetic fibres such as glass, as depicted in Table 1 (Garkhail *et al.* 2000; Joshi *et al.* 2004; Malkapuram *et al.* 2008). The benefits of natural fibres often outweigh the disadvantages. Natural fibres offer weight reduction and cost savings, because of its low density and availability. In addition, it degrades easily and it offers ease of machinability with minimum tool wear. Though it has low thermal stability, poor compatibility, and poor resistance to environment. But if these unique technical problems posed by the natural fibres can be resolved, natural fibres can replace glass fibre and other synthetic fibres even in outdoor applications.

Table 1. Advantages and Disadvantages of Natural Fibres (Garkhail *et al.* 2000; Joshi *et al.* 2004; Malkapuram *et al.* 2008)

Advantages	Disadvantages
Lightweight	Low thermal stability
Biodegradability	Lack of interfacial adhesion
Ease of machinability	Quality variation
Non toxic	Poor resistance to environment
Availability and low cost	Poor compatibility with polymer matrix
Non-abrasive	
Less dependency on non-renewable energy	
Low pollutant emission	
Energy recovery	

A comparison between natural and glass fibres is shown in Fig. 2 (Wambua *et al.* 2003; Sanyang *et al.* 2016b). While natural fibres degrade easily, synthetic fibres are difficult to naturally degrade; carbon dioxide emission and the requirement for non-renewable energy for the production of glass fibre is much higher than natural fibres (Joshi *et al.* 2004). These are some of the reasons why natural fibres are increasingly replacing synthetic fibres in many applications.

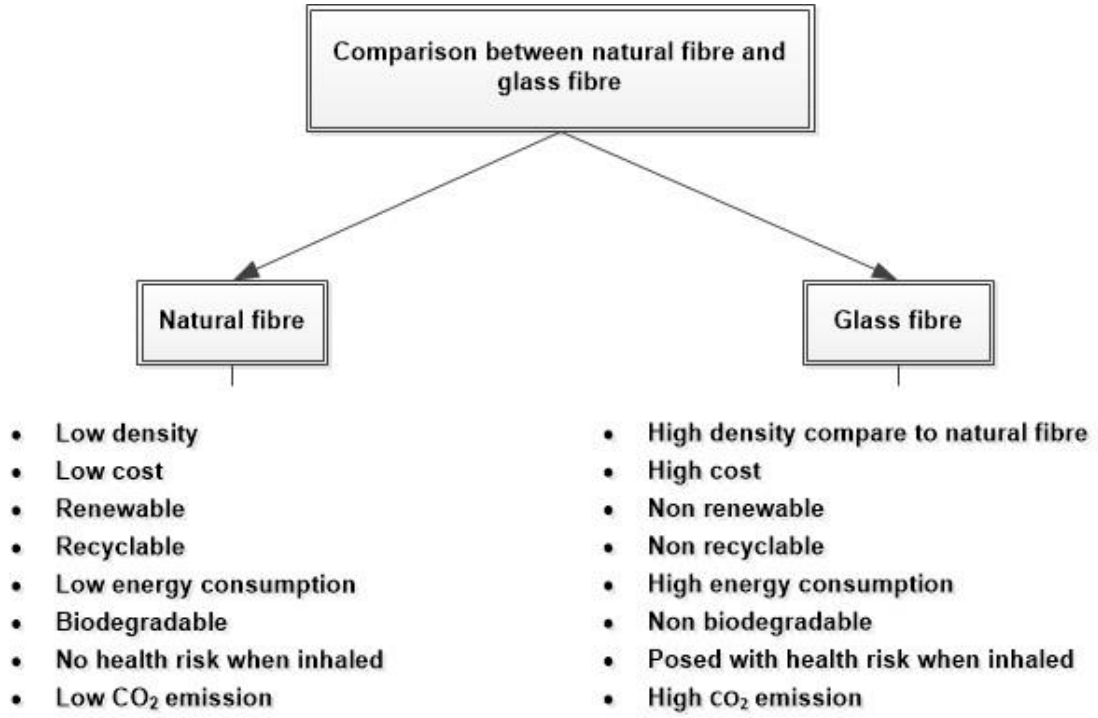

Fig. 2. Comparison between natural fibre and glass fibre (Wambua *et al.* 2003; Sanyang *et al.* 2016b)

HISTORY OF SUGAR PALM TREE AND ITS FIBRE

The sugar palm tree (*Arenga pinnata*) is a member of the Palmae family. This plant is normally found in hot, humid parts of the Asian tropics, and it has the widest range of uses, which makes it a multipurpose palm species. Many of the more than 3000 tropical and subtropical palm species can be classified as multipurpose (Mogea *et al.* 1991). Sugar palm trees are found in tropical South and Southeast Asia, including Indonesia, Malaysia, India, Philippines, Papua New Guinea, North Australia, Thailand, Burma, Vietnam, *etc.* (Dransfield *et al.* 2005; Sahari *et al.* 2012). In Malaysia, sugar palm trees are found along the rivers in rural areas; its plantation growth covers approximately 892 hectares (Sahari *et al.* 2012b). In Indonesia, there are about 150 vernacular names for this multipurpose palm, including but not limited to "*kelapa*", "*merah*", "*semut*", "*gomuti*", "*kaong*", and "*aren*" (Heyne 1950); in Malaysia it is called "*enau*" or "*kabung*" (Ishak *et al.* 2013).

The sugar palm tree grows close to human settlement and sometimes grows in the secondary forest to the border of primary rainforest from the lowland up to the altitude of about 1400 m (Mogea *et al.* 1991). Its trunk is solitary, straight, and usually 15 to 20 m in height and up to 65 cm in diameter (Sanyang *et al.* 2016b). It has large leaves up to 6 m long. The trunk is covered with black fibrous hair, commonly known as *Ijuk* or *Injuk*. The fibres found along its height have different chemical compositions and hence vary in properties (Ishak *et al.* 2012). The sugar palm tree starts to flower between the age of 10 to 12 years, but early flowering can occur as early as 5 to 6 years. The tree dies after a lifetime of 12 to 20 years depending on the harvest environment (Mogea *et al.* 1991; Suwartapradja 2003). Figure 3 shows pictures of sugar palm trees (Wanderer 2010).

Fig. 3. Sugar palm tree and its trunk loaded with fibre (Wanderer 2010)

Table 2. Traditional and Modern Uses of Sugar Palm Trees (Mogea *et al.* 1991; Sahari *et al.* 2012b)

Tree Part	Uses
Ijuk fibre (wrapped around trunk)	Rope, filters, brooms, and roofing
Young leaves	Eat as vegetable (fresh or cooked)
Root	Herb to cure bladder stone, insect repellent, boards, tool handles, and water pipes
Steam core	Sago, fibres
Fruits bunch/Sap/male inflorescences	Juice, sugar syrup (*beluluk*), palm sugar (*gula aren*), drink, raw material (nectar sweetener), wine, vinegar, alcohol, biofuel
Pitch of leaf's rachis	Drinking cup
Young leaves	Cigarette paper, salads
Seed, tip of its stem	Eat as vegetables
Leaflets midrid	Brooms, baskets
Endospore of unripe fruit	Cocktail/sweetmeat
Flower	Source of nectar honey production
Timber	Hard outer part of the trunk is used for flooring, furniture, musical instrument (drum), *etc*.
Hairs at the base of the leaf sheath	Tinder for igniting fire

Uses of Sugar Palm Tree

Sugar palm is a great source of food, beverages, biofibres, biopolymers, and biocomposites (Sahari *et al.* 2012b). It is a popular plant because of its year-round food production, especially in the dry season when other food sources are scarce in rural areas. Virtually all of its parts can be used. Traditionally, this palm is used principally for sugar, and the tree sap can be processed into *gula aren/gula kawong/gula beureum* (Suwartapradja 2003). It is used as a drink or as a raw material for nectar sweetener (Mogea *et al.* 1991) or is fermented to produce biofuel, namely bioethanol (Ishak *et al.* 2012), yielding up to 20,160 litres of bioethanol per hectare per year (Sahari *et al.* 2012b). However, its seed and the tip of its stem are edible vegetables. The shaggy material at the base of the leaves makes an excellent rope, as it is strong and resists decay. Table 2 summarises the uses of sugar palm trees.

Sugar Palm Starch

The starch from the sugar palm trunk can be utilised as a biopolymer, which can be used with natural fibre to produce a "biocomposite" or "green composite". The starch is abundant inside the trunk of the sugar palm tree, which when modified by either plasticization or blending can be used as a biopolymer (Imre and Pukánszky 2013). The use of the starch as a biopolymer will greatly reduce dependency on petroleum-based polymers. Sahari *et al.* (2012a, 2013b) explored the potential of using sugar palm starch as a biomatrix by plasticizing the starch with glycerol. The effect of the plasticiser on the physical, thermal, and mechanical properties was studied. Sahari *et al.* (2013a) produced a biocomposite (*i.e*., sugar palm fibre as reinforcement and biopolymer from starch of sugar palm tree as matrix) with increased tensile strength and modulus and flexural strength and modulus. Impact strength increased with fibre loading, but the elongation at break decreased. In the same composite, the water absorption decreased with increased fibre loading, which was similar to moisture content. Sugar palm fibre has better water resistance than biopolymers from sugar palm starch, but this can be overcome with further research by modification of the biomatrix. The starch from sugar palm tree can be plasticized and formed into a film for food packaging (Sanyang *et al.* 2015, 2016a).

Fig. 4. Sugar palm tree, its fibre, and SEM image of single fibre (Bachtiar *et al*. 2008; Ishak *et al*. 2013)

Sugar Palm Fibre

Another important part of this tree is its fibre. Figure 4 shows a sugar palm plant, a fibre bunch, and an SEM image of the fibre (Bachtiar *et al.* 2008; Ishak *et al.* 2013). The full length of its trunk is completely covered with black fibre locally known as *gomuti* fibre or *Ijuk*. The traditional or early applications of this fibre includes paint brushes, septic tank base filters, door mats, carpet, ropes, chair/sofa cushions, brooms, road construction, roofing materials, and shelters for fish breeding (Mogea *et al.* 1991; Suwartapradja 2003; Bachtiar *et al.* 2008). The modern application of sugar palm fibre includes fabrication of a small boat (Misri *et al.* 2010); a hybridised glass fibre and sugar palm fibre reinforced unsaturated polyester composite was used for the small boat manufacturing using the hand lay-up technique. Razak and Ferdiansyah (2005) used SPF as reinforcement in concrete, and the addition of fibre increased the toughness characteristics of the concrete compared with plain concrete. With research and development, the application will go beyond boat manufacturing and concrete reinforcement as other areas of applications are identified.

The quality of sugar palm fibre makes it an export product. From 1976 to 1985, approximately 2400 tonnes of SPF, at a value of about 1.5 million USD, were exported annually to West Germany only from Java, Indonesia (Mogea *et al.* 1991). Unlike other natural fibre, sugar palm fibre does not require chemical or mechanical extraction, as this fibre is naturally wrapped around the trunk.

CHARACTERIZATION OF SUGAR PALM FIBRE (SPF)

Utilising SPF as a reinforcement in polymer matrix is a relatively new application. To recognise the strengths and weaknesses of natural fibre composites, it is necessary to comprehend the physical, mechanical, and thermal properties of the fibres. Research on SPF and its composites started around the year 2005, but these properties are not well established. A few reports on SPF physical, chemical, mechanical, and thermal properties will be reviewed critically (Bachtiar *et al.* 2010; Ishak *et al.* 2012; Sahari *et al.* 2012; Ticoalu *et al.* 2014).

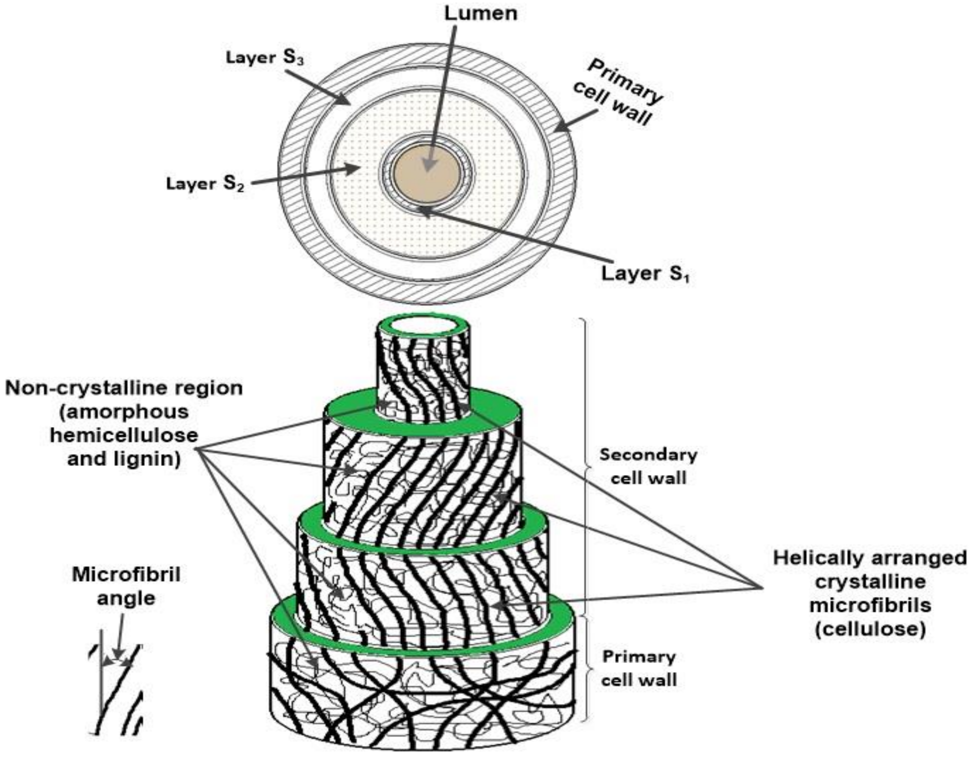

Fig. 5. Structure of natural fibre (redrawn from Kalia *et al.* (2009) and Rong *et al.* (2001))

Structure and Chemical Composition of SPF

The chemical composition, chemical structure, and cell structure arrangement of natural fibre are very important. These parameters are responsible for the performance and durability of the natural fibre composites in their various applications. The structural arrangement of plant fibre is shown in Fig. 5. The natural fibre has a complex layered structure, where the outermost primary wall encloses the secondary wall. The secondary wall consists of three layers namely, S1, S2, and S3. The middle layer S2 is the thickest (approximately 80% of the total thickness of the fibre) and is responsible for the mechanical properties of the fibre (Rong *et al.* 2001). The layers consist of helically wound cellulose microfibrils, which are bound together by an amorphous lignin serving as a binder (Kalia *et al.* 2009); while hemicellulose acts to strengthen the cell wall by interaction with cellulose and lignin *via* non-covalent forces (Scheller and Ulvskov 2010). Evidently, there is covalent bonding between lignin and hemicellulose (Lawoko *et al.* 2005). Cellulose and lignin are most important two fibre components, as hemicellulose burnt out at an early stage of thermal analysis. This has motivated Birnin-Yauri *et al.* (2016b) to conduct a study by combining a cellulose-rich fibre and lignin-rich fibre to form a hybrid composite. The results showed synergistically improved properties. The crystal structure, microfibril angle, size of lumen, size of the crystalline region, porosity, and void have a strong influence on properties of natural fibres and its composite (Baley 2002; Kalia *et al.* 2011).

The chemical composition of natural fibres generally reveals the content of cellulose, hemicellulose, lignin, pectin, ash, and other naturally occurring constituents (Kalia *et al.* 2009; Rong *et al.* 2001). Hemicellulose, cellulose, and lignin are the three main components of lignocellulose material, comprising 10 to 25 wt.%, 31 to 70 wt.%, and 7 to 26 wt.%, respectively (McKendry 2002; Li *et al.* 2007; Yang *et al.* 2007). These constituents of plant fibre contain the stored chemical energy, which varies from plant to plant (McKendry 2002). Looking at the proportion of the composition, the cellulose is the main constituent of natural fibre, and it provides mechanical strength (Reddy and Yang 2005). Unlike cellulose, hemicellulose does not give significant contributions to the strength of the natural fibre, but it binds microfibrils of the fibre (Reddy and Yang 2005). In addition, cellulose is a highly crystalline structure with about 80% crystalline region (Ho *et al.* 2012). Lignin is an amorphous complex of polymers of phenylpropane units, and it functions as an encrusting agent or simply as a matrix (Han and Rowell 1997).

The chemical compositions of sugar palm fibre were determined in previous research (Sahari *et al.* 2012; Ishak 2013). Sahari *et al.* (2012) investigated the chemical composition of sugar palm fibre, as shown in Table 3. The fibre can be obtained from four different morphological parts, *i.e.*, frond, bunch, trunk, and *Ijuk* (the surface of the trunk). The compositional percentage of cellulose, holocellulose, and lignin are all within the range of natural fibres stated by McKendry (2002). Frond has the highest percentage of cellulose, followed in decreasing order by bunch, *Ijuk*, and trunk. *Ijuk* fibre contains almost 90% of the total fibres from the sugar palm tree.

Table 3. Chemical Composition of Sugar Palm Fibre Obtained from Different Morphological Parts of the Tree

Composition	Sugar Palm Frond	Sugar Palm Bunch	*Ijuk*	Sugar Palm Trunk
Cellulose (%)	66.5	61.8	52.3	40.6
Holocellulose (%)	81.2	71.8	65.6	61.1
Lignin (%)	18.9	23.5	31.5	46.4
Moisture (%)	2.7	2.7	7.4	1.5
Extractive (%)	2.5	2.2	4.4	6.3
Ash (%)	3.1	3.4	4.0	2.4

Source: Sahari *et al.* 2012

Ishak *et al.* (2013) investigated the chemical composition of the *Ijuk* fibre obtained from different heights of the trunk, *i.e.*, 1, 3, 5, 7, 9, 11, 13, and 15 m, as shown in Table 4. The cellulose, hemicellulose, and lignin contents increased with the increase of sugar palm tree height and were directly proportional to tensile strength, modulus, and elongation values. Cellulose and hemicellulose content decreased at the upper part of the tree, which was attributed to the juvenile stage of the fibre. It was concluded that biological degradation took place at the bottom part of the tree where brown or broken fronds were seen. The use of fibre around a dead palm frond as reinforcement in a composite should be avoided because the fibres in that location are biologically degraded, leading to broken polymeric chains and inferior properties (Ishak *et al.* 2012). Fibres between 5 to 11 m showed optimum properties, based on the chemical composition of the fibre. The fibres within this range are free from sand and mature. Chalid *et al.* (2015) studied the chemical composition of *Ijuk* fibre and found 28.32 wt.% lignin, 51.44 wt.% cellulose, and 23.88 wt.% hemicellulose, which was in agreement with results obtained by Sahari *et al.* (2012) and Ishak *et al.* (2013).

Table 4. Chemical Composition of Sugar Palm Fibre Obtained from Different Heights of the Tree

Composition	Height (m)							
	1	3	5	7	9	11	13	15
Cellulose (%)	37.3	49.4	55.3	56.6	56.8	55.8	54.4	53.4
Hemicellulose (%)	4.7	6.1	7.4	7.7	7.9	7.9	7.9	7.5
Lignin (%)	17.9	18.9	20.9	20.5	23.6	23.0	24.3	24.9
Moisture (%)	5.36	8.64	7.92	8.37	8.19	7.72	8.12	8.70
Extractive (%)	2.49	2.02	1.71	1.41	1.35	1.48	1.21	0.85
Ash (%)	30.9	14.0	5.8	4.2	2.1	4.1	4.0	4.3

Source: Ishak *et al.* 2013

Table 5. Chemical Composition of SPF in Comparison with Other Natural Fibres

Type of fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture (%)	Extractive (%)	Ash (%)
SPF	37.3 - 66.5	4.7 - 20.6	17.9 - 46.4	1.5 - 8.7	0.85 - 6.3	2.1 - 30.9
Abaca	56 - 63	15 - 17	7 - 9	–	–	3
Coir	32 - 42	0.15 - 0.25	40.45	5	–	2
Kenaf	31 - 57	8 - 23	15 - 21.5	–	–	2 - 5
Flax	64.1 - 73.8	11 - 16.7	2.0 – 2.9	7.9 - 10	–	–
Hemp	57 - 77	14.0 - 22.4	3.7 - 13	–	–	10.8
Jute	45 - 71.5	13.6 - 22.4	12 - 26	–	–	0.5 - 2
ramie	68.6 - 76.2	5 - 16.7	0.6 - 0.7	–	–	8
Sisal	47 - 78	10 - 24	7 - 11	–	–	0.6 - 1
Oil palm	33.75	30.4	22.9	8.14	-	4.78

Source: (Baley 2002; Li *et al.* 2007; Ayrilmis *et al.* 2011; Kabir *et al.* 2012; Sahari *et al.* 2012; Ishak *et al.* 2013; Omrani *et al.* 2015; Birnin-Yauri *et al.* 2016a)

The chemical constituents of natural fibres vary, and these variations can be observed even in fibres from the same plant. Several factors are responsible for these variations, including soil quality, weather condition, geographical location, morphological part of the plant, maturity/age of the plant, extraction methods, and test equipment used (Koronis *et al.* 2013). Tables 3 and 4 show variations in the chemical constituents of SPF. In comparison, there are variations reported by Ishak *et al.* (2013) and Sahari *et al.* (2012). The former analysed the chemical composition obtained from a different height of trunk, while the latter considered fibres from different morphological parts, *i.e.* frond, bunch, trunk, and *Ijuk*. The chemical composition of sugar palm fibre in comparison with other established natural fibres is compiled in Table 5 based on data from various authors (Baley 2002; Li *et al.* 2007; Ayrilmis *et al.* 2011; Kabir *et al.* 2012; Sahari *et al.* 2012; Ishak *et al.* 2013; Omrani *et al.* 2015). The properties and percentage of each chemical constituent of natural fibre contribute significantly to the overall engineering properties of the natural fibre. Compared with other natural fibres, the cellulose content of SPF, which mainly provides strength, is higher than that of coir and kenaf, but it is within the range of abaca, flax, and jute. This is a strong justification that sugar palm fibre is a potential reinforcement in natural fibre composites. Sugar palm fibre is qualified because its cellulose, hemicellulose, and lignin contents are well within the range of established natural fibres.

Table 6. Comparative Physical Properties of SPF and Other Natural Fibres

Fibre	Density (g/cm^3)	Diameter (µm)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
SPF (Ijuk)	1.4	81 – 500	276	3.847	12.8
Sisal	1.33 – 1.5	50 – 300	511 – 635	9.4 – 22	2 – 2.5
Coir	1.2	100 – 450	248	4.94	30
Ramie	1.5	46 – 53.2	400 – 938	61.4 - 128	3.6 – 3.8
Hemp	1.47	17 – 23	690	70	2 – 4
Jute	1.3 – 1.46	20 – 200	393 - 773	26.25	1.5 – 1.8
Flax	1.4 – 1.5	11.3 – 23	1,339	54.08	3.27
Kenaf (Bast)	1.45	70 – 250	295	53	1.6

Source: (Mwaikambo and Ansell 2006; Dhakal *et al.* 2007; Li *et al.* 2007; Kalia *et al.* 2009; Defoirdt *et al.* 2010; Ku *et al.* 2011; Martin *et al.* 2013; Ticoalu *et al.* 2014)

Physical and Mechanical Properties

The sugar palm fibre known as *Ijuk* is black/brown in colour, and its various physical and mechanical properties have been reported in the literature. The density and diameter of SPF were determined by several authors using different methods, but the results come with variations from one author to another. This can be attributed to the known quality variations of natural fibres and equipment/procedure employed for the measurement. Razak and Ferdiansyah (2005) reported a diameter range of 300 to 500 µm. Suriani *et al.* (2007) reported a range of 94 to 370 µm, which is close to the findings of Bachtiar *et al.* (2010), who got a range of 99 to 311 µm using weighing in conjunction with formula method. In another study, Sahari *et al.* (2012) reported a value of 212 µm for the diameter of *Ijuk* fibre. Ticoalu *et al.* (2014) found the diameter to be 81 to 313 µm, and Chalid and Prabowo (2015) reported 376 µm. Based on the reported work from literature, *Ijuk* fibre has a diameter range of 81 to 500 µm, which is comparable with coir and sisal.

The physical properties of SPF and well-established natural fibres such as jute, ramie, sisal, coir, and kenaf were compiled in Table 6 (Paul *et al.* 1997; Baley 2002; Mwaikambo and Ansell 2006; Bogoeva-Gaceva *et al.* 2007; Dhakal *et al.* 2007; Li *et al.*, 2007; Munawar *et al.* 2007; Kalia *et al.* 2009; Defoirdt *et al.* 2010; Ku *et al.* 2011; Martin *et al.* 2013; Ticoalu *et al.* 2014). Sugar palm fibre has values similar to other natural fibres. The density of SPF is comparable with that of hemp, flax, and kenaf but higher than coir. The moisture content of SPF is between 5.36 to 8.7%, as reported by Ishak *et al.* (2012), which is much lower than that of jute, sisal, coir, and bagasse, which have 12, 11, 10, and 8.8 %, respectively (Rowell 2008).

The tensile properties of natural fibre, namely, tensile strength, modulus, and elongation, are determined through a single fibre tensile test. In single fibre testing, the test length should be critically chosen to avoid too many flaws within the gauge length; the strength of single fibre decreases with increased gauge length, which was verified for coir, bamboo, and jute fibres by Defoirdt *et al.* (2010). For better prediction of the performance of the natural fibres, the data in Table 6 were used to determine the specific tensile strength and specific tensile modulus of various natural fibres, which are shown in Fig. 6.

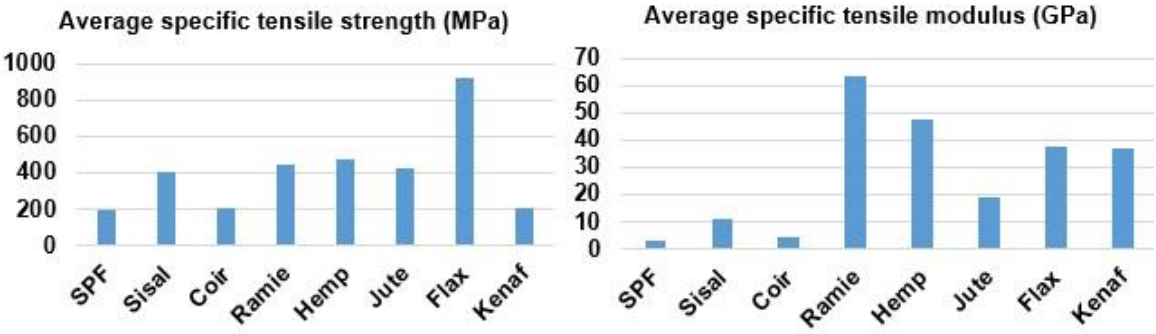

Fig. 6. Average specific tensile strength and modulus of natural fibres

The specific tensile strength and specific stiffness are important indicators for mechanical performance. These values were depicted in Fig. 6, and it can be observed that sugar palm fibre can be a true reinforcing material in natural fibre composite because of its competitive average specific strength and specific modulus values compared with other natural fibres like coir and kenaf. Natural fibres with high specific strength and modulus have a special advantage in an application where weight is a critical factor, such as automotive applications. Flax, ramie, and hemp have superior mechanical performance in comparison with other natural fibres.

Thermal Properties

The most frequently used thermal analysis technique is thermogravimetric analysis (TGA). It is widely used to characterise materials by measuring their change in mass as a function of temperature. A natural fibre is thermally stable over a temperature range where there is no significant change in fibre mass. This range can be seen in the thermograph of the change in weight *versus* temperature. Usually, this temperature range is used to determine the natural fibre composite processing temperature. A thermal analysis of sugar palm fibre by Ishak *et al.* (2012) showed that SPF decomposed in phases in the following order: evaporation of moisture (45 °C to approximately 123 °C), followed by the decomposition of hemicellulose (210 to 300 °C), cellulose (300 to 400 °C), lignin (160 to

900 °C), and ash (1,723 °C). The decomposition of lignin starts much earlier than hemicellulose and cellulose and covers a wide temperature range. It occurs at a lower rate, which makes it difficult to decompose (Yang *et al.* 2007). In another thermal analysis by Ticoalu *et al*. (2014), the first loss in weight was ~ 4.1% at 48.1 °C for moisture evaporation, while hemicellulose starts to decompose at a temperature of 248 °C with a weight loss of ~ 17.5%. The major weight loss of ~ 44.1% was during the decomposition of cellulose at 324.8 °C. Based on this analysis, sugar palm fibre had an onset thermal degradation of 222.8 °C, which means that the processing temperature of sugar palm composite should be below this temperature to avoid degradation of the fibre during processing.

LIMITATIONS OF SUGAR PALM FIBRE

Sugar palm fibre and other natural fibres have many positive reasons for being used as reinforcing fillers in polymers, at the same time there are also several limitations associated with them. The hydrophilic nature of natural fibres is the major limitation compared to conventional reinforcing fibres like glass, carbon, and aramid. The other limitations are depicted in Fig. 7. When these drawbacks are resolved, natural fibres will be the leading reinforcement fillers in the field of composite materials because of their competitive advantages.

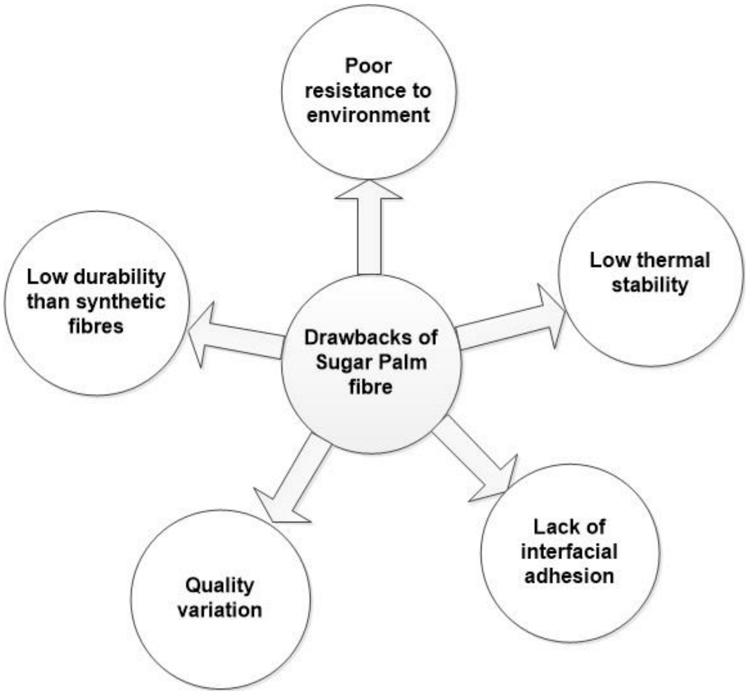

Fig. 7. Bottlenecks of natural fibres as reinforcement in polymer (Faruk *et al.* 2014; Senwitz *et al.* 2016)

The most worrisome drawback of natural fibre composite is lack of interfacial adhesion between the filler and the polymeric matrix. In a given composite, the matrix has a role of transferring the load to the reinforced fibre through shear stresses at the interface of the matrix and fibre. Load-bearing capacity of a composite largely depends on the bonding between the natural fibre and the matrix. Having poor adhesion at the interface will weaken the fibre and consequently yield poor mechanical properties that will render the material incapacitated in many applications. A potential solution to this problem is to treat the fibre or modify the matrix for better adhesion (Bachtiar *et al.* 2008; Leman *et al.* 2008; Ishak *et al.* 2009; Leman *et al.* 2010; Sapuan *et al.* 2010; Bachtiar *et al*. 2011; Ishak *et al.* 2011a; Ticoalu *et al.* 2014). Poor resistance to water absorption is another drawback of natural fibres, which limits their usage to indoor applications. This phenomenon is a result of the hydroxyl group of the natural fibre, which tends to react with water molecules by hydrogen bonding, making it degrade and swell easily when exposed to the changes in the environment (Lin *et al.* 2002). Furthermore, moisture absorption by natural fibres affects their physical, mechanical, and thermal properties (Dhakal *et al.* 2007).

Natural fibres are known to have low thermal stability, as most fibres start to degrade above 200 °C. The processing temperature and operating conditions need to be carefully selected to avoid decomposition of lignocellulose materials, which will deter optimum performance of the composite. SPF has a thermal stability up to 222.8 °C, as reported by Ticoalu *et al.* (2014), and 210 °C, as reported by Ishak *et al.* (2012). Compared with coir as reported by Rosa *et al.* (2009) the lignocellulose materials start to degrade at 190 °C. A similar investigation on thermal properties of coir and sisal by Bismarck *et al.* (2001) showed that these fibres had an onset thermal degradation between 190 and 230 °C. The low degradation temperature of natural fibres is a serious challenge because these temperatures are mostly inadequate for processing composite with thermoplastic materials that have high processing temperatures (Azwa *et al.* 2013). Natural fibres are of low durability compared with synthetic fibre, but this can be improved considerably with treatment (Pickering *et al.* 2015). These drawbacks can result in composites with undesirable properties that make them be unsuitable for certain applications. Fibre treatments and matrix modification solve some of these drawbacks.

TREATMENT OF SUGAR PALM FIBRE

Natural fibres are generally hydrophilic due to the presence of hydroxyl groups throughout its structure, especially in cellulose and hemicellulose. To improve the properties and performance of natural fibres, it becomes necessary to impart hydrophobicity to the natural fibres. Several treatment methods had been studied in order to improve the interfacial adhesion property between fibres and surrounding matrix and concurrently to reduce water absorption of the fibres. The treatment methods of natural fibres are many and each has its own effect on the properties of the natural fibres. The most common treatments are alkaline, silane, acetylation, benzoylation, and permanganate treatments. These treatments were outlined by Kabir *et al.* (2012).

Alkaline Treatment

Alkaline treatment, also known as mercerization, is the most common treatment method of natural fibres. Its simplicity and effectiveness make it a popular approach for treating natural fibre with sodium hydroxide aqueous solution to improve fibre-matrix adhesion and reduce moisture absorption. Alkaline treatment is beneficial in reducing the moisture absorption and increasing the interfacial bonding between sugar palm fibre and matrix (Bachtiar *et al.* 2008; Sapuan *et al.* 2010; Ticoalu *et al.* 2014). This modification usually affects the morphology, mechanical properties, and thermal degradation of SPF. In all of these published reports, the diameter of the SPF decreased, which increased the aspect ratio. The increase in aspect ratio results in rough topography, which yields better adhesion and mechanical properties. Bachtiar *et al.* (2008) reported that both tensile strength and modulus were improved by treating SPF with 0.25 M and 0.5 M NaOH, though inconsistent results were noticed at high concentration, which was attributed to fibre damage. Sapuan *et al.* (2010) showed that 0.25 M NaOH was optimum, as it yields better results and improved flexural strength compared with untreated fibre. In another work, SPF was treated with 5% and 10% NaOH, which increased the tensile strength by 34.3% and 29.3%, respectively (Ticoalu *et al.* 2014). The samples in this experiment were soaked in diluted NaOH for 2 h, followed by rinsing and drying at 80 °C for approximately 4 h.

Seawater Treatment

Seawater is an effective surface treatment of natural fibres at virtually no cost. This can be done by soaking the fibre in seawater for some days. Seawater naturally contains 35 g of salt in every 1000 g or 1 litre of water. The treatment is achieved by removing the outer layer of hemicellulose and pectin, thereby improving interfacial bonding between fibre and matrix. Leman *et al.* (2008) showed that fibre treated with seawater for 30 days had its tensile strength improved by 67.26% compared with untreated fibre. Ishak *et al.* (2009) showed that the impact and flexural strength of SPF increase significantly after a soaking period of 30 days in seawater. Recently, Rashid *et al.* (2016) further confirmed that treatment of SPF with seawater yield positive improvement based on the physical and morphological characterization results presented.

Pre-impregnation Process

Matrix pre-impregnation is another process that promotes interfacial adhesion bonding between the hydrophilic fibre and hydrophobic polymer (Fung *et al.* 2003; Herrera-Franco and Valadez-Gonzalez 2004, 2005). The pre-impregnation process exploits the low viscosity of the incurred resin, and this facilitates the impregnation of the matrix into the pores and surface of the reinforcing fibre. The effect of impregnating SPF with thermoset resin on physical and mechanical properties was studied by Ishak *et al.* 2011b. Based on this research, the effect of the process was more pronounced on the physical properties rather than mechanical properties, which were marginally improved. Two thermoset resins, unsaturated polyester and phenol formaldehyde, were used for the vacuum resin impregnation process, but the latter showed superior results. There was significant improvement in physical properties, namely, water absorption and moisture content were recorded, but no significant changes in specific gravity. The effect of impregnation pressure was studied Ishak *et al.* (2011a); an impregnation pressure of 600 mmHg was optimum to improve both physical and tensile properties.

SUGAR PALM FIBRE REINFORCED POLYMER COMPOSITE

SPF/Thermoplastic Composite

The early research on SPF-reinforced thermoplastic composite was done by Sapuan and Bachtiar (2012). The researchers studied the tensile strength and modulus of sugar palm fibre reinforced high impact polystyrene (HIPS) with five different fibre loadings (10, 20, 30, 40, and 50%). With increased fibre loading in the HIPS matrix, the tensile modulus increased at the expense of the tensile strength, which was attributed to poor compatibility of the fibre and matrix. The result was supported by SEM analysis that showed fibre pull-out, signifying poor adhesion between the hydrophilic fibre and hydrophobic high impact polystyrene. Bachtiar *et al.* (2012) studied mechanical and thermal properties of untreated SPF reinforced HIPS. The composite showed a high thermal stability compared with the control and good mechanical properties. Zahari *et al.* (2015) determined the water resistance and mechanical properties of SPF reinforced polypropylene. The fibre and polypropylene matrix were mixed at 190 °C using a roll mill mixer. The compound was crushed using a plastic granulator to get pellets. The pellets were vacuum dried and injection-moulded to produce the composite samples. The result indicated improved tensile strength and modulus with silane treatment, but the elongation at yield was almost constant for both treated and untreated fibres. Water absorption increased at high fibre contents but stabilised after 10 days.

SPF/Thermoset Polymer Composite

Thermoset polymers are dominantly used as matrices with sugar palm fibre. Epoxy, unsaturated polyester, and phenol formaldehyde are the reported matrices used by various researchers. Epoxy has excellent properties that make it the best matrix in many composites; some of these properties are good adhesion, low moisture absorption, and ease of processing (Mar 2008). Leman *et al.* (2005) fabricated SPF reinforced epoxy composites using a hand lay-up process. The impact strength of the long fibre reinforced epoxy composite was higher than chopped fibre reinforced epoxy composite. The tensile properties of the same composite increased with fibre loading of 10 and 15% but decreased with 20% fibre loading (Sastra *et al.* 2006). The effect of accelerated ageing on SPF reinforced epoxy was studied (Ali *et al.* 2010). The results indicated that the aged composite had an increase in tensile strength up to 50.4%, but its impact strength declined by 6.33%. Sahari *et al.* (2011) studied water resistance of SPF reinforced unsaturated polyester, and the composite was produced using compression moulding with 30% fibre loading. The results indicated that SPF reinforced unsaturated polyester had lower values of water absorption and thickness swelling of 0.65 and 0.76%, respectively.

Other Matrices Reinforced with SPF

Increasing environmental concern has generated interest in biocomposites and the development of environmentally friendly material that is fully biodegradable. The biocomposite is obtained by blending biodegradable polymers with lignocellulose fibres, which yields a 100% biodegradable composite. Biopolymers or biodegradable polymers can be classified as agro-polymers (starch, protein, *etc*.) and biodegradable thermoplastic (poly (lactic acid) PLA). The latter are also called biopolyesters and are mainly obtained from renewable resources. SPF has been used with both agro-polymers and biodegradable thermoplastic. Environmentally friendly composites derived from sugar palm tree have been studied (Sahari *et al.* 2013a). The biocomposite was produced using SPF and plasticized starch from sugar palm trees. The biomatrix was produced by mixing 70% starch with 30% glycerol. With increased fibre loading, the biocomposite showed increased tensile strength, tensile modulus, flexural strength, flexural modulus, and impact strength but decreased elongation at break. Similarly, the water absorption and moisture content decreased with increased fibre loading. Lignocellulose decomposition started at a lower temperature of 150 °C, which indicated low thermal stability.

Polylactic acid (PLA) is a bio-derived polymer used as a matrix material, while *Ijuk* fibre was used as reinforcing material by Chalid *et al.* (2015) to fabricate biocomposites using hot compression moulding. In this composite, the best values of tensile strength and modulus were obtained with 10% fibre loading. Because SPF is a natural fibre and 100% biodegradable, it accelerates the biodegradability when combined with PLA (Chłopek *et al.* 2010).

PROPERTIES OF SPF REINFORCED POLYMER COMPOSITE

Determination of Water Resistance

Natural fibre reinforced polymer composites absorb moisture in a humid environment or when immersed in water. The moisture absorbed by the composite causes it to swell and develop dimensional instability. This is attributed to the hydrophilic nature of the natural fibres. These behaviours are major challenges that limit the interior applications for composites, except for treated fibre or hybridised composite. Fibre contents and lack of surface treatment of the fibre are the two major causes of water uptake in natural fibre reinforced polymer composites (Azwa *et al.* 2013). Fibre content or loading is directly proportional to water uptake; higher fibre loading allows more moisture absorption in the composite. This strong relationship between water absorption and fibre weight fraction was seen in a study of hemp fibre reinforced polypropylene (Hargitai *et al.* 2008). A composite with 30% fibre fraction had only 7% water absorption, whereas for 70% fibre weight fraction, the water uptake increased to 53%.

Leman *et al.* (2008) reported that untreated SPF reinforced epoxy composite plate with 20% fibre loading has higher moisture absorption than 10% fibre loading composite plates. The plates were both immersed in a controlled water bath at 40 °C for 33 days. Bachtiar *et al.* (2012) reported moisture absorption behaviour of SPF-HIPS composites. The specimens were immersed in a water at 25 °C for 24 h. At 10%, 20%, 30%, 40%, and 50% fibre loading, the moisture absorption was 0.9%, 1.3%, 1.5%, 2.8%, and 3.9%, respectively; thus, increased fibre loading resulted in increased moisture absorption. The water absorption in natural fibre composite increases with the increase of fibre loading. This result contradicts the case of SPF reinforced biopolymer from sugar palm starch (SPS) as a matrix (Sahari *et al.* 2013a). The results indicate that with an increase of SPF loading, the moisture absorption of the composite decreases. This phenomenon was attributed to the fact that SPF is more hydrophobic than plasticized sugar palm starch.

The moisture absorption characteristic of sugar palm fibre reinforced polymer composites was reviewed. The percentage of moisture uptake clearly increases as the fibre volume fraction increases. This was attributed to the presence of high cellulose in the SPF. This drawback is the main reason for it being precluded in exterior applications. Surface treatments and matrix modification are considered the general solutions to this weakness in natural fibres, which can also be applied to SPF.

Mechanical Properties

The mechanical properties of SPF reinforced polymer composites—namely, tensile properties, flexural properties, and impact properties—are noticeably altered by the fibre weight fraction, fibre treatment, and/or matrix modification. Table 7 shows the tensile properties of the novel sugar palm fibre reinforced polymer composites and the matrices used. Many natural fibre composites show variation or inconsistent values in these properties, which were attributed to the source of the fibre, processing, or manufacturing techniques.

Table 7. Tensile Properties of Sugar Palm Fibre Reinforced Polymer Composites

Type of fibre / Fibre form / Treatment	**Fibre loading wt.%**	**Matrix**	**Tensile strength (MPa)**	**Tensile modulus (MPa)**	**Authors**
Hand lay-up process					
SPF/long fibre/untreated	15	Epoxy	49.6	1196.0	Sastra *et al*. (2006)
SPF/chopped/untreated	15	Epoxy	32.6	1164.0	Sastra *et al*. (2006)
SPF/woven/untreated	10	Epoxy	51.7	1255.8	Sastra *et al*. (2006)
SPF/long fibre/untreated	10	Epoxy	50.4	1074.9	Suriani *et al*. (2007)
SPF/long fibre/untreated	15	Epoxy	43.7	1161.4	Suriani *et al*. (2007)
SPF/long fibre/untreated	20	Epoxy	30.9	1254.5	Suriani *et al*. (2007)
SPF/chopped/untreated	10	Epoxy	33.8	1040.4	Suriani *et al*. (2007)
SPF/chopped/untreated	15	Epoxy	31.6	1118.2	Suriani *et al*. (2007)
SPF/chopped/untreated	20	Epoxy	30.5	1202.3	Suriani *et al*. (2007)
SPF/woven/untreated	10	Epoxy	51.7	1010.3	Suriani *et al*. (2007)
SPF/long fibre/NAOH (0.25M) 1h	10	Epoxy	49.9	3780.0	Bachtiar *et al*. (2008)
SPF/chopped/fresh water 30 days	15	Epoxy	21.2	-	Leman *et al*. (2008)
SPF/chopped/seawater 30 days	15	Epoxy	23.0	-	Leman *et al*. (2008)
Injection moulding process					
SPF/chopped/untreated	10	PP	17.57	361.32	Zahari *et al*. (2015)
SPF/chopped/silane treated	10	PP	20.21	1051.84	Zahari *et al*. (2015)
SPF/chopped/untreated	20	PP	18.36	720.24	Zahari *et al*. (2015)
SPF/chopped/silane treated	20	PP	20.27	1066.30	Zahari *et al*. (2015)
SPF/chopped/untreated	30	PP	19.71	1052.40	Zahari *et al*. (2015)
SPF/chopped/silane treated	30	PP	23.00	1098.51	Zahari *et al*. (2015)
Compression moulding process					
SPF/chopped/untreated	10	HIPS	26.2	1516	Sapuan *et al.* (2012)
SPF/chopped/untreated	20	HIPS	23.2	1618	Sapuan *et al.* (2012)
SPF/chopped/untreated	30	HIPS	19.3	1706	Sapuan *et al.* (2012)
SPF/chopped/untreated	40	HIPS	24.3	1662	Sapuan *et al.* (2012)
SPF/chopped/untreated	50	HIPS	28.5	1652	Sapuan *et al.* (2012)
SPF/chopped/untreated	16	HIPS	23.2	1620	Oumer *et al*. (2014)
SPF/chopped/untreated	26	HIPS	19.3	1710	Oumer *et al*. (2014)
SPF/chopped/untreated	35	HIPS	24.3	1660	Oumer *et al*. (2014)

The mechanical properties of SPF-reinforced polymer composites have been studied (Sastra *et al.* 2006; Suriani *et al.* 2007; Bachtiar *et al.* 2008; Sapuan and Bachtiar 2012; Oumer and Bachtiar 2014; Zahari *et al.* 2015). Different fibre forms, *i.e.*, long, chopped, and woven, were used with different types of polymer matrices.

Irrespective of processing methods and other factors, woven sugar palm fibre reinforced epoxy presented a superior value of tensile strength of 51.7 MPa (Suriani *et al.* 2007). Long fibre with 10 wt.% loading reinforced epoxy had the highest tensile modulus of 3780 MPa (Bachtiar *et al.* 2008), which was attributed to the mercerization treatment of SPF. This showed that chemical treatment offers better physical and mechanical properties. In the same experiment, 0.25 M NaOH and a 1-h soaking time were the optimised alkaline treatment parameters. A similar trend was noticed with treatments using seawater and fresh water; the mechanical properties were slightly improved (Leman *et al.* 2008; Ishak *et al.* 2009).

The tensile modulus was considerably increased when high impact polystyrene was used as the matrix (Sapuan and Bachtiar 2012; Oumer and Bachtiar 2014). The addition of SPF to HIPS decreases the tensile strength, and a similar trend was reported by Antich *et al.* (2006) for sisal fibre reinforced HIPS. Generally, irrespective of fibre loading, the fibre form in SPF reinforced polymer composites has a tensile strength of 17.57 to 51.7 MPa and tensile modulus of 361.32 to 3780 MPa.

The cited work reflected that with an increase of fibre fraction, the tensile strength increases to a maximum value and later drops. A similar trend is observed for the tensile modulus, though in some research the values either fluctuate or decrease. Some factors contributing to this variation are fabrication method, fibre degradation, and lack of interfacial adhesion. The evaluation of the performance of natural fibre composites should not be restricted to mechanical properties. The best is to make use of ternary diagram as proposed by Koronis *et al.* (2013), which includes specific strength, specific stiffness and cost per weight for evaluating the performance of particular composites.

THERMOGRAVIMETRIC ANALYSIS OF SPF-REINFORCED COMPOSITE

The growing interest in using SPF as reinforcement in polymer composites has motivated the investigation of the thermal behaviour of the composites, though not much has been reported on thermogravimetric analysis of SPF-reinforced polymer composites. Bachtiar *et al.* (2012) reported TGA and DTG thermograms of SPF-reinforced HIPS composite. The thermograms were obtained at a heating rate of 20 °C/min, and the samples were observed from 30 to 600 °C. High thermal stability of the composite was noticed with degradation commencing at 329 °C and completed at 447 °C. The results indicated that the thermal stability increases with the increased fibre loading. The same trend was noticed in a fully biodegradable composite of SPF and biopolymer from sugar palm starch (Sahari *et al.* 2013a).

The first mass loss occurs between 30 to 100 °C for the moisture evaporation, while the major constituents decomposed between 150 and 380 °C. Thermal stability of the composite increases with the increased fibre loading, which was clearly seen from the percentage of the residue or ash of the various composites. The findings of the thermal analysis of SPF-reinforced polymer is supported by the work of Santafé *et al.* (2011). They reported that the TG curves of untreated coir reinforced polyester composite at different fibre loading (10, 20, and 30 wt.%) showed an onset of degradation at approximately 340 °C and completed at 450 °C.

APPLICATIONS AND POTENTIALS OF NATURAL FIBRE COMPOSITES

To minimise dependency on exhaustible fossil products and reduce environmental impact, composites from renewable resources have been very promising mostly in the automotive and aerospace industries. In automobiles, the dominant use of natural fibre composites by far is in the interior parts. They are utilised in the interior because natural fibre composites absorb moisture in a humid climate and tend to swell. Swelling leads to tiny cracks forming between the fibre and matrix, allowing water molecules to infiltrate. This phenomenon makes the composite degrade and lose strength easily. Despite these drawbacks, natural fibre composites are preferred over synthetic fibre composites. German car manufacturers are in the forefront for utilising natural fibre composites in many components of automobiles including door panels, seat shells, shelf trim panels, roof liners, and package trays. There are few exterior automotive components being used including tire covers, under-the-hood radiator end tank, car disc brakes, and under-body panels (Hill *et al.* 2012). Other applications include the aerospace, furniture, consumer goods, and package industries. Polypropylene based composites produced by compression moulding, injection moulding, or thermoforming extruded sheet are favoured in automotive applications (Puglia *et al.* 2005).

Sugar palm fibre has started gaining acceptance in engineering applications. A new material, a hybrid of sugar palm fibre and glass-reinforced unsaturated polyester, was used to manufacture a small boat (Fig. 8(a); Misri *et al.* 2010). The hybrid small boat had its mechanical properties increased significantly with a tensile modulus of 1840.6 MPa and impact strength of 2.471 kJ/m^2. In addition to the increased mechanical properties, the weight was reduced by 50% with the substitution of sugar palm fibre in place of glass fibre (Sanyang *et al.* 2016b). Sugar palm fibre *(Ijuk)* reinforced thermoset was studied in helmets as well, as shown in Fig. 8(b) (Zaid 2009). The helmet passed Malaysian standard (MS) test conducted by SIRIM QAS INT., Sdn. Bhd. In another development, a zinc roofing sheet was lined with sugar palm fibre as sound proofing material (Imran 2015). The same material could be utilised potentially for sound proofing engine covers. With ongoing research, more potential uses of sugar palm fibre and its composites will be explored and used in many applications.

Fig. 8. SPF product development (a) small boat and (b) safety helmet (Zaid 2009; Misri *et al.* 2010)

CONCLUSIONS

1. Sugar palm trees are a novel source of natural fibre with ecological and economic advantages. This low density, biodegradable fibre can be used with a polymeric material to produce partially biodegradable composites.
2. The starch from sugar palm tree can be utilised to produce biopolymer, which can be used with natural fibre to produce a “biocomposite” or “green composite”. It can also be chemically modified by plasticizing into films for food packaging.
3. The sugar palm sap is used as a drink or as a raw material for nectar sweetener. It is also fermented to produce biofuel, namely bioethanol.
4. Properties of the sugar palm fibre are within the range of natural fibres, which make it qualify as reinforcement in natural fibre composites. Based on the available information, sugar palm fibre has a diameter of 81 to 500 µm, cellulose content of between 37.3 to 66.5%, hemicellulose content of 4.7 to 20.6%, and lignin content of 17.9 to 46.4%.
5. Further research on sugar palm fibre should focus on the influence of SPF incorporation on the properties of synthetic fibres, for possible used in structural applications.

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