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REVIEW PAPER

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Mechanical properties of sugar palm lignocellulosic fibre reinforced polymer composites: a review

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Abstract The significant reduction in petroleum resources and the growth of global environmental awareness on the use of conventional plastics are the motivating factors to accept natural fibres as green materials. Lignocellulosic fibre-reinforced polymer biocomposites have attracted considerable attention from engineers and researchers because of their sustainable nature and wide availability. Sugar palm is an emerging crop grown in Malaysia and Indonesia and is regarded as a significant candidate lignocellulosic fibre in biocomposites. Sugar palm fibres are mainly made up of cellulose, which leads to outstanding mechanical properties. From a literature review, no comprehensive review paper has been published on the mechanical behaviour of sugar palm lignocellulosic fibre biocomposites to provide a good source of literature for doing further research on this topic to consider them construction and building materials. The present review concentrates on recent work on the properties of sugar palm lignocellulosic fibres, starches, and nanofillers and their fabrication as biocomposites.

Keywords Sugar palm fibre · Thermoplastic · Thermoset · Mechanical properties · Biocomposites

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Introduction

Natural fibres have been widely applied since early times. Nowadays, the implementation of natural fibres in composites has received global attention. Polymeric composites are usually made up of polymer resin reinforced with fibre. Natural fibres are sourced from animal parts, plants and minerals. Various lignocellulosic fibres, such as kenaf (Asyraf et al. 2021c), ramie (Yu et al. 2009), flax (Chandrasekar et al. 2019), hemp (Nayak et al. 2020), pineapple leaf (Asim et al. 2018) and roselle (Radzi et al. 2019a), have been used for numerous composite engineering applications. The production of lignocellulosic fibres has been progressively growing, given that they are easily available and present great advantages in terms of eco-friendliness. Lignocellulosic fibre biocomposites also exhibit high sustainability, good formability, renewability, abundance, low cost, thermal insulation properties, sufficient energy requirements and safety towards health (Ali et al. 2021; Roslan et al. 2021; Asyraf et al. 2022c). Furthermore, lignocellulosic fibres have good potential in composites due to their chemical composition. They are made up of cellulose, pectin, hemicelluloses, lignin, waxes and water-soluble substances. The chemical constituents of lignocellulosic fibres may differ even within the same plant species. They highly depend on geographical factors, plant parts, plant growth conditions and fibre extraction technique (Ishak et al. 2012; Oladele et al. 2018; Asyraf et al. 2021a).

The capability of fibres depend on various factors, including the mechanical strength of fibres, surface topography, fibre polarity and presence of reactive locations (Dai 2006; Ramesh 2016). Despite the promising features of lignocellulosic fibres, drawbacks, such as lack of thermal stability, lowered impact properties, high water absorption and strength degradation, are also highlighted (Asyraf et al. 2021b, a). As a solution to these issues, lignocellulosic fibres can be improved through hybridising with either synthetic or other lignocellulosic fibres. Lignocellulosic fibres have high specific strength and low density and are highly valuable in several industrial applications, such as civil construction (Amir et al. 2021), safety equipment (Asyraf et al. 2020b), packaging (Ilyas et al. 2020) and household products (Mazani et al. 2019).

Sugar palm fibres (SPFs) are increasingly well-known throughout the world, and considerable research has been conducted and contributed to the progress of green technology for automotive, sports, food packaging and furniture industries (Mansor et al. 2014; Pil et al. 2016; Yusup et al. 2019; Asyraf et al. 2022b). SPFs grasp much attention owing to their potential as polymer reinforcements in the biocomposite industry. Various researchers have demonstrated the higher mechanical performance of sugar palm biocomposites than that of other types of lignocellulosic fibre polymer composites; hence, they are suitable for high-structural performance lignocellulosic fibre-reinforced polymer biocomposites (Ishak et al. 2011). SPFs as reinforcement phases are prominent materials for conventional products, such as brushes, brooms and roofs (Ishak et al. 2013). Sugar palm biocomposites can eventually replace petroleum-based composite materials in various known industrial applications, such as cross arms in transmission towers (Asyraf et al. 2022a), body armour (Nurazzi et al. 2021b), tissue engineering (Sharma et al. 2021), automotive components (Azammi et al. 2018).

Recently, available review papers have been reporting more on mechanical performance of general fibre-reinforced polymer composites with different types of fibre reinforcement. However, these review papers are lacking in comprehensive information, especially on sugar palm biocomposites. Therefore, this review article focuses on the findings of mechanical analyses such as tensile, flexural, and impact tests to measure various sugar palm biocomposites. This comprehensive review also apprises the recent works on the thermal properties of SPFs and SPF biocomposites for various applications in different sectors. This review is also expected to gather the information on the mechanical behaviour of SPF-reinforced polymer composites with numerous influential factors, such as fibre loading, fibre sequence with the use of two or more fibres, polymer resins, and fibre modifications. Thus, sugar palm biocomposites are proposed to be used as innovative environmental, agricultural, manufacturing, and consumer products, which could promote the green technology.

Sugar palm and its current commercial products

Sugar palm, a tall tree (8–15 m high in average) named *Arenga pinnata*, belongs to the subfamily of Arecoideae. The tribe of Caryoteae is widely grown in humid parts of the Asian tropics at the elevation from 700 to 1200 m with an annual temperature of 19–27 °C in areas with rainfall of 500–1200 cm, from South Asia to South-East Asia and from Taiwan to the Philippines, Indonesia, Papua New Guinea, India, North Australia, Malaysia, Thailand, Burma and Vietnam (Sahari et al. 2012b; Ishak et al. 2013; Muda and Awal 2021). It is a natural forest species which can reach maturity within 10–12 years, with 150 local names, such as *A. pinnata*, areng palm, black fibre palm, gomuti palm, aren, irok, bagot and kaong (Sahari et al. 2012b; Sanyang et al. 2016a). In Malaysia, it is known as either enau or kabung, which can be found widely along the rivers and bushes in the rural areas of Bruas-Parit (Perak), Raub (Pahang), Jasin (Melaka) and Kuala Pilah (Negeri Sembilan), with approximately 809 ha plantation land area in Tawau (Sabah) and 50 ha sugar palm plantation in Benta (Pahang) (Sanyang et al. 2016a; Huzaifah et al. 2017). Figure 1 shows a sugar palm tree.

A sugar palm tree is classified as one of the most versatile multipurpose trees amongst more than 3000 palm species of the tropics, given that almost all parts of the tree can be used for various purposes and for making numerous local products; hence, they have economic value for the people in rural areas (Sahari et al. 2012b; Ishak et al. 2013; Sanyang et al. 2016a; Azhar et al. 2019). The products from a sugar palm tree can be divided into four groups: fibres (all fibre-based products), trunks (starches), flowers (sap for making sugar) and fruit. Twelve products based on sugar palm trees, namely, fibres, starches, roofs, ropes, brooms, brushes, bottle brushes, vinegar, fruits, liquid sugar, refined sugar and block sugar, have been developed (Sapuan 2018). The main product from a sugar palm tree is sap, traditional sweet cold drink (known as nira enau), which is collected from male flower bunches (locally called *nira*) (Sapuan 2018; Azhar et al. 2019). Several products can be produced from sap, including sugar palm block (known as gula enau), sugar palm syrup, fine sugar, vinegar (using a fermentation process) and bioethanol (used as a raw material for the production of various products, such as chemical products, solvents, pharmaceuticals, cosmetics, medicines and beverages) (Sahari et al. 2012b; Ishak et al. 2013; Sapuan 2018). Four litres to five litres of sap can be collected from each bunch twice a day, depending on the fertility of the trees and the number of male bunches present in a tree (Sapuan 2018). Sugar palm can produce sugar 2–4 times higher than sugarcane from its sap (Terryana et al. 2020). Palm sugar is believed to be an alternative sweetener and a more nutritious sugar compared with sugarcane, considering that palm sugar usually does not undergo any purification process or at least has no synthetic chemical to bleach the colour, resulting in a sugar with potential nutritional benefits due to phytochemical compounds, such as polyphenols (Victor and Orsat 2018). A sugar palm tree bears fruit (has an oval shape, spikes and a clear or white colour) that can be processed for food and is traditionally named *beluluk*, *buah kabong* or *kolang kaling* amongst the Malaysian in accordance with certain areas. This fruit is one of the popular side dishes and desserts in the Malay community, and it is widely used in the food industry (Sahari et al. 2012b; Sapuan 2018).

Fig. 1 Sugar palm tree (Bachtiar et al. 2011a, b). Creative Common CC BY license

SPFs and Sugar Palm Starch (SPS) are the two products with registered trademarks (Sapuan 2018). SPFs can compete with most lignocellulosic fibres in the market, such as coir, oil palm, kenaf, cotton and jute, owing to their outstanding mechanical properties (Sanyang et al. 2016a). They have several names, such as aren, gomuti and black, and are locally known as *ijuk* fibres (Hraběl et al. 2018). Each sugar palm tree can yield approximately 15 kg of *ijuk* fibres (Sahari et al. 2012b; Sapuan 2018). These fibres are traditionally utilised by the local people to make brooms, brushes, filters, door mats, cushions, ropes, roofing materials and handicrafts for making *kopiah* (Sahari et al. 2012b; Sanyang et al. 2016a; Hraběl et al. 2018;

Sapuan 2018). SPFs are extremely durable, even when in contact with seawater. As a result, they have a great potential to be used as reinforcement materials in the fabrication of biocomposites (Sanyang et al. 2016a; Huzaifah et al. 2017; Sapuan 2018). Currently, several SPF biocomposite products are being developed, such as a hybrid unsaturated polyester (UPE) composite boat made from the combination of SPFs and glass fibre, which reduces the weight of the boat by up to 50% due to the utilisation of SPFs in place of glass fibre (Fig. 2) (Ishak et al. 2013; Sanyang et al. 2016a). Sugar palm is also a potential source of starch (usually obtained from the core of a nonproductive matured sugar palm tree's trunk) for developing biodegradable polymers (Ishak et al. 2013; Sanyang et al. 2016a). One sugar palm tree can produce 50–100 kg of starch (Sahari et al. 2012b; Sanyang et al. 2017). The products that could be made from these materials, such as flushable undergarment liners, shopping bags, packaging films and medical delivery devices and systems, present high potential (Sanyang et al. 2017; Ilyas et al. 2018). SPS is considered a green material and can be utilised to make green composites when reinforced with lignocellulosic fibres (Sahari et al. 2012b; Huzaifah et al. 2017; Ilyas et al. 2018). Various advantages of using SPFs and SPS in green composites have been reported; the advantages include decreasing the dependence on petroleum products, reducing the negative environmental impact of synthetic materials and developing sugar palm as a new industrial crop in near future in tropical South-East Asian countries, such as Malaysia, resulting in improved socioeconomic status of rural people by providing further job opportunities (Sanyang et al. 2016a).

A sugar palm tree has many other traditional applications. The young fresh leaves have been used in salad, cooked for soup, fried or transformed into cigarette wrappings (Sahari et al. 2012b; Muda and Awal 2021). Sugar palm has been used in folk medicine. Palm sap can be used for indigestion, rashes and pulmonary irritation; in the Philippines, fermented palm sap is consumed to avoid tuberculosis (Sahari et al. 2012b). Sugar palm roots are believed to break down kidney and bladder stones when boiled with water (Sahari et al. 2012b; Muda and Awal 2021).

Fig. 2 Sugar palm biocomposite boat (Ishak et al. 2013). Reproduced with permission from Ishak et al. 2013. Copyright 2013 Elsevier

SPF

Sugar palm is locally well-known as *ijuk* and can be found in Malaysia and Indonesia. SPFs are presently considered waste products from sugar palm cultivation, in which sugar palm is a multipurpose plant grown in these countries. Owing to the large demands from consumers, SPFs have been amongst the major products from a sugar palm tree. The fibres are versatile and can be applied to a wide range of products, including ropes, roofs, brushes, brooms, pultruded components, mats and hammocks, as shown in Fig. 3. A sugar palm tree produces fibre before flowering after approximately 5 years of plantation. In general, the SPFs are black in colour and can have a length of up to 1.19 m. The diameter of SPF is usually 94–370 µm, with an overall density of 1.26 kg/m^3 (Bachtiar et al. 2010b). The fibre's strength is affected by altitude and the age of the sugar palm tree. The SPFs can be heat resistant at a maximum of 150 °C, with a flash point at 200 °C (Sastra et al. 2006). After harvesting the SPFs from its tree, it can be graded with five classes from A to E depending on its length and thickness (Ishak et al. 2013). Bachtiar et al. (2011a, b) reported the tensile strength, tensile modulus and elongation at break of SPF to be 190.29 MPa, 3.69 GPa and 19.6%, respectively.

SPFs are resilience towards seawater, and it could be embedded in marine applications (Ishak et al. 2009). Ishak et al. (2011) characterised the tensile properties of SPF from different heights of sugar palm trees (1, 3, 5, 7, 9, 11, 13 and 15 m). The outcomes showed that the fibre from the upper part of the tree (palm frond) exhibited higher tensile modulus and strength than that from the bottom part. Moreover, the elongation at break and toughness of the lignocellulosic fibre seemed to increase with the tree height. Table 1 displays the

Fig. 3 The products of SPF

Table 1 Tensile properties of SPFs from different parts of sugar palm tree (Sahari et al. 2012a, 2013)

Fibre	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
Ijuk	276.6	5.9	22.3
Trunk	198.3	3.1	29.7
Bunch	365.1	8.6	12.5
Frond	421.4	10.4	9.8

mechanical properties of SPF from various parts of sugar palm trees. According to Sahari et al. (2012a, b), the tensile properties of frond SPF were the highest, followed by those of bunch, ijuk and trunk fibres. These findings were influenced by their cellulose contents. The cellulose component provided strength and stability to the cell walls to maintain the structural integrity of the fibres. The different heights of trees led to a difference in their chemical compositions. The aging process of wood-based materials is also affected by the chemical composition of the fibre (Asyraf et al. 2020a; Alias et al. 2021). The fibre located at 1 m height from the ground contains many impurities, such as silica, which indicated a higher ash content (30.92%) compared with that of the fibres obtained from the tree's upper parts (2.06–5.84%). This observation can be found from the FT-IR analysis conducted by Ishak et al. (2010). Owing to its remarkably high ash content, the fibre from 1 m height had lower moisture content (5.36%) than other fibres (3–15 m height), which were in the range of 7.72–8.7%. Table 2 displays the chemical composition of SPF depending on the heights of sugar palm trees.

Table 2 Chemical composition of SPFs from various heights of sugar palm tree (Ishak et al. 2010)

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

In terms of thermogravimetric (TGA) analysis, the SPFs from various heights of sugar palm trees were characterised by Bachtiar et al. (2012). From their findings, four phases of decomposition of the fibres started with the evaporation of moisture, followed by the breakdown of hemicelluloses, cellulose and lignin, and the last component left was their ash. The thermal degradation of these components was found in the ranges of 45–123 °C, 210–300 °C, 300–400 °C, 160–900 °C and 1723 °C. The TGA curves displayed that the fibre with 1 m height from ground had higher thermal stability than fibres of 3–15 m due to the high ash content.

Table 3 Comparison of mechanical properties with other common natural fibres (Sanyang et al. 2016a)

Natural fibre	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)
Sugar palm (frond)	421.4	10.4	9.8
Henequen	430–580	–	3–4.7
Ramie	500	44	2
Sisal	600–700	38	2–3
Hemp	550–900	70	1.6
Abaca	980	–	–
Flax	800–1500	60–80	1.2–1.6

Limitations of SPFs

SPFs are classified as a natural lignocellulosic fibre, mainly composed of cellulose, hemicellulose, lignin and ash, like other natural fibres such as kenaf. It is composed of approximately 37.3–66.48% cellulose. The cellulose component allows the fibre to have good mechanical performance, as shown in Table 3. Moreover, the relative amount of cellulose in SPFs is lower than that of other established natural fibres, as displayed in Table 4. In this case, cellulose acts as a vital structural component in natural fibres to retain durability and structural integrity (Chen et al. 2014).

Another major drawback of SPF is that it has a high content of lignin and ash. This drawback leads to the lack of compatibility of the fibre when reinforcing in a polymer matrix because it reduces the reactive area to bind the composites (Nurazzi et al. 2021a). The improper compatibility of fibre/matrix in composites would allow laminate crack propagation due to the air voids between the fibre interface and matrix, which consequently reduces the impact and tensile properties of the composites (Azman et al. 2021). A comprehensive action, such as fibre treatments, has to be taken on SPFs to increase the cellulose content of the fibre, remove impurities and enhance its mechanical properties.

On the basis of the preceding discussion, the mechanical performance of SPF composites presents several issues. Up to this date, no comprehensive review paper has been published on the properties of SPFs and SPF biocomposites, as well, as well as the factors which influence their mechanical performance. Thus, further elaboration on the factors affecting the mechanical behaviour of SPFs and SPF composites based on recent findings is provided in the subsequent section.

Table 4 Chemical composition of SPFs in comparison with other natural fibres (Mukhtar et al. 2016)

Natural fibre	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Moisture content (%)	Extractive (%)	Ash (%)
Sugar palm	37.5–66.5	4.7–20.6	17.9–46.4	1.5–8.7	0.85–6.3	2.1–30.9
Ramie	68.6–76.2	5.0–16.7	0.6–0.7	–	–	8.0
Sisal	47.0–78.0	10.0–24.0	7.0–11.0	–	–	0.6–1.0
Hemp	57.0–77.0	14.0–22.4	3.7–13.0	–	–	10.8
Abaca	56.0–63.0	15.0–17.0	7.0–9.0	–	–	3.0
Flax	64.1–73.8	11.0–16.7	2.0–2.9	7.9–10.0	–	–

Key issues affecting mechanical properties of SPF reinforced polymer composites

Background: issues and problems of SPFs

Cellulose and lignin are the two main building blocks in lignocellulosic fibres. The cellulose component acts as structural support and offers mechanical performance for the fibres. The mechanical properties of lignocellulosic fibres depend on various aspects, including the volume fraction of fibre, fibre length, fibre orientation, and surface compatibility between the fibre and the matrix. Previous literature reported that the flexural and tensile properties of sugar palm biocomposite highly depend on the sugar palm loading (Maisara et al. 2019). Furthermore, the fibre/matrix adhesion, volume fraction of fibre, and fibre size play vital roles in determining the biocomposite strength, stiffness and toughness (Johari et al. 2020).

The major issue associated with lignocellulosic fibre biocomposites in terms of mechanical properties is the lack of compatibility between the fibre and matrix (Danso 2017; Rashid et al. 2017a; Ayu et al. 2020). Many literature found that most natural fibre-reinforced polymer composites have several issues such as high moisture absorption, poor fibre/matrix bonding adhesion, and low melting point (Kuan et al. 2021). The main issue of SPF-reinforced composites is interfacial bonding, which still needs to be clarified further. Interfacial bonding can be divided into interdiffusion bonding, mechanical interlocking, electrostatic bonding, and chemical bonding as shown Fig. 4. Due to low compatibility between SPFs and their matrix, the mechanical performance of the

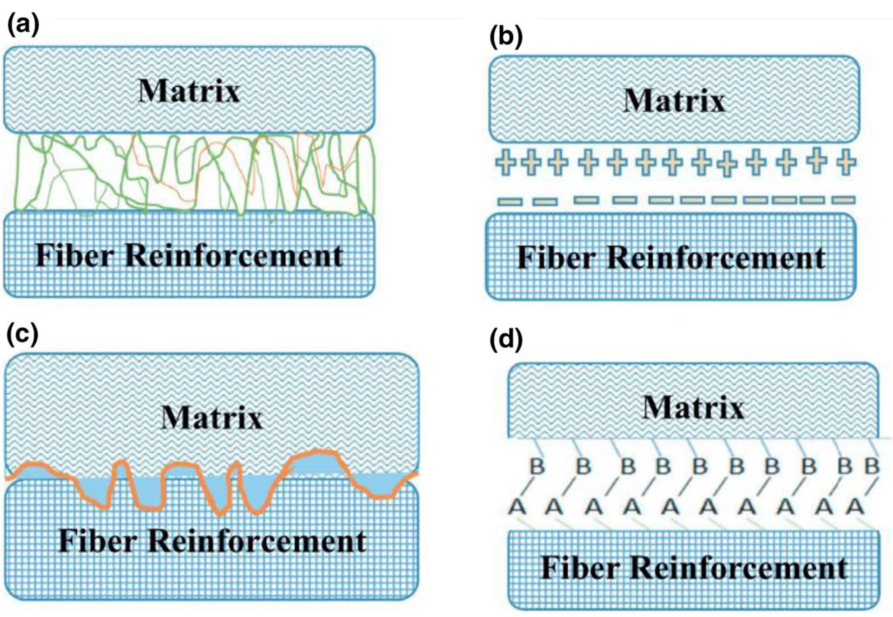

Fig. 4 Types of interfacial bonding: **a** molecular inter diffusion, **b** electrostatic bonding, **c** mechanical interlocking, and **d** chemical bonding (Latif et al. 2019)

final composites is significantly reduced. The non-polar nature of lignocellulosic fibre causes the lack of fibre dispersion, inadequate adhesion, and decline in the fibre performance. Consequently, it is likely to agglomerate in the matrix due to the hydrogen bonds of the hydroxyl groups, resulting in poor fibre dispersion within the matrix and poor fibre/matrix interaction (Shesan et al. 2019). Since the polymer matrix exhibits a nonpolar hydrophobic property, the matrix exacerbates the dispersity of the polar fibre, which is hydrophilic by nature. The main hindrances in pure lignocellulosic fibre biocomposites are the scarcity of interfacial adhesion, low melting point, and poor resistance to moisture uptake, leading to the initiation of composite microcracks. The microcracks lead to the reduce in mechanical performance, thereby resulting in the less attractive use of lignocellulosic fibre-reinforced biocomposites (Hamidon et al. 2019). For example, Chaiwong et al. (2019) reported the highest tensile strength in 5% NaOH-treated OPF–wheat gluten green composites, which shows a good interfacial adhesion between the lignocellulosic fibre and the biopolymer matrix. The effectiveness of composites reinforced with lignocellulosic fibres relies on the fibre–polymer matrix interface and the tendency of transferable stress to the fibres from the matrix.

Pretreatments either using chemical or physical approaches usually shows fine perfection in tensile and compression properties due to the enhanced interfacial linkage or fibre–matrix adhesion. In this case, the lead contributor towards enhanced composite strength and toughness is the fibre/matrix adhesion. The effective stress distribution of fibre and matrix would regulate the brittleness and toughness of composites. An optimum volume ratio of fibre would also significantly contribute to maximising the mechanical properties due to high aspect ratio that effectively transfers stress to the matrix (Neoh et al. 2011). Scientists have stated that manufacturing and processing techniques allow remarkable mechanical behaviour of lignocellulosic fibre biocomposites. Chemical treatment techniques for lignocellulosic fibres help clean the fibre surface, elevate the surface roughness of fibres, and lessen the moisture absorption process (Mustafa and Dauda 2014). Chemical modifications on lignocellulosic fibre surface include acetylation, peroxide treatment, graft copolymerisation, benzoylation, peroxide treatment, etherification, permanganate treatment, mercerisation, and use of coupling agents such as silane (Aisyah et al. 2021).

Recent literatures on effect of fibre treatments of SPFs in its polymer matrix

A number of works have recognised that chemically treated SPFs possess significantly enhanced mechanical properties in contrast to untreated SPFs. Most workers have discovered that their SEM micrographs show that treatment aids the fibre by removing the outer layers that contain impurities (ash, wax and pectin) and less nodes. Researchers have also proposed significant improvement in the tensile, flexural and impact strengths and stiffness of SPF biocomposites by using several types of polymers (Rashid et al. 2016; Izwan et al. 2020; Mukhtar et al. 2020). Several fibre treatments on SPFs, including seawater treatment, mercerisation, benzoylation and combined treatments, were conducted by various researchers.

Seawater treatment is considered a low-cost and efficient treatment technique to improve natural fibre surfaces. It is commonly done by soaking the fibres in seawater for a couple of days. Seawater is typically composed of 0.035% salt. Many researchers have reported that this treatment removes the outer layer of hemicellulose and pectin, which later improves the fibre/matrix interaction. Ishak et al. (2009) discovered that the flexural and impact strengths for 30 wt% SPF loading of seawater-treated sugar palm/epoxy biocomposites were improved by 7.35 and 5.06%, respectively. Maisara et al. (2019) evaluated the influence of fibre length and seawater treatment on the mechanical behaviour of sugar palm/UPE biocomposites. They demonstrated that treated SPF composites with 15 cm fibre length presented increased tensile and flexural strengths at 18.33 MPa.

Alkaline treatment or mercerisation is a typical method to treat natural fibres, especially SPFs. Owing to its simplicity and effectiveness, it has become a popular approach in treating natural fibres by using a sodium hydroxide aqueous solution to achieve good compatibility of fibre/matrix and decrease composites' moisture absorption. This treatment is useful in reducing the water uptake rate and enhancing the SPF/matrix interfacial bonding (Mohd Nurazzi et al. 2017; Syaqira et al. 2020). This modification is highly effective in improving the topography, mechanical properties and thermal degradation of SPFs. Many studies have reported surface modification of SPFs via alkali treatment. Table 5 summarises the conditions used by various researchers for mercerisation of SPFs.

Bachtiar et al. (2009) explored the evident impacts of mercerisation of SPFs on biocomposite properties by using a hand lay-up method. The impact strength of SPF/epoxy biocomposites increased by 28.69% via 0.5 M NaOH treatment of SPFs for 8 h. Another study has illustrated that the interfacial adhesion between fibres and matrix directly affects the tensile properties of lignocellulosic fibre-reinforced polymers (thermoplastics and thermosets). Researchers have found that the alkalisation treatment with sodium hydroxide improves the mechanical properties of SPFs compared with those of untreated SPFs, with an optimum value of 6% NaOH showing good results for chemical treatment methods (Mohammed et al. 2016; Atiqah et al. 2018c). Moreover, the tensile properties of sugar fibres are affected by NaOH solution immersion time and concentration rate (Bachtiar et al. 2010b, 2014). Treatment of SPFs with 6% NaOH would aid the lignocellulosic fibre to split its bundles into very fine fibres, resulting in effective entrance of polymeric resin and causing high intertwining of the fibres in the matrix (Atiqah et al. 2019). This condition leads to improved interfacial adhesion, which promotes enhanced fibre/matrix adhesion.

Silane treatment of fibres is usually conducted through immersion of 2 wt% silane solution for several hours. The weight percentage of fibres, dissolved for hydrolysis in a mixture of methanol–water (90/10 w/w), was considered in silane treatment. After the treatment, the fibres were thoroughly cleaned using distilled water and oven-dried at 60 °C for 72 h to remove any moisture effect from the fibres (Atiqah et al. 2017). A lab-scale experiment carried out by Atiqah et al. (2018a) showed that a silane-treated SPF/TPU composite exhibited better tensile strength than alkali-treated, alkali–silane-treated and untreated SPF/TPU composites. The microsurface of the silane-treated SPFs was roughened to induce mechanical interlocking with the TPU matrix.

Table 5 Alkali treatment of SPFs from previous studies

Concentration	Soaking time	References
4 and 6%	1 h	Bachtiar et al. (2013)
0.25 M and 0.5 M	1, 4, and 8 h	Bachtiar et al. (2008)
6%	3 h	Atiqah et al. (2018a)
5 and 10%	2 h	Ticoalu et al. (2014)

In addition to the above-mentioned treatments, previous researchers have also treated SPFs with a sodium bicarbonate solution (Mukhtar et al. 2020). The researchers prepared a solution with 10 wt% bicarbonate. Later, they soaked the fibres in the solution for 5 days. Afterwards, the fibres were washed completely with distilled water to remove excess bicarbonate and oven-dried for 24 h. Mukhtar et al. (2019) demonstrated that the tensile properties of sugar palm/polypropylene composites were increased via sodium bicarbonate treatment. The improvement in tensile performance was said to be due to the sodium bicarbonate-treated SPFs that removed the excess impurities on the fibre, and the sodium-treated SPF composite recorded 58.76 MPa against 53.01 MPa for the untreated SPF composite.

Benzoylation is carried out after alkaline treatment by using benzoyl chloride. The process starts with a pretreatment, including cleaning and drying actions within several days, followed by using 18% NaOH solution on the fibre for 30 min. Later, the treated fibre was suspended in 10% NaOH solution and agitated well with 50 ml of benzoyl chloride for 15 min. Subsequently, the fibre was removed and washed with distilled water (Wang et al. 2003, 2007). A study has indicated the mechanisms that enhance the interfacial adhesion of sugar palm–epoxy biocomposites by employing benzoyl chloride-treated SPF-reinforced epoxy biocomposites (Safri et al. 2020). In sum, chemical treatment of lignocellulosic fibres considerably upgrades the tensile strength and modulus of formulated sugar palm–epoxy biocomposites (Safri et al. 2020).

Mohammed et al. (2018) evaluated the influence of microwave treatment with mercerisation at 6% NaOH on SPF/polyurethane biocomposites. They determined that the 70 °C microwave treatment allowed enhanced interfacial adhesion between the lignocellulosic fibre and thermoset matrix, which subsequently led to increases in Young's modulus and tensile strength up to certain maximum values of the sugar palm biocomposites. Other researchers have reported that the mechanical and interfacial bonding properties of sugar palm/polyurethane biocomposites are enhanced by modification of sugar palm nonwoven by alkali-silane treatment (Atiqah et al. 2018a). The nonwoven-treated sugar palm–polyurethane biocomposites have favourable and better properties compared with a single treatment (6% NaOH and 2% silane) fibre composite prepared by the same compression moulding. The silane treatment allows to roughen the fibre surface, which later introduces mechanical interlocking (Xie et al. 2010; Ramamoorthy et al. 2015; Atiqah et al. 2018b). A comparison study between alkaline and seawater treatments on SPF/phenolic biocomposites was conducted by Bushra et al. (Rashid et al. 2017b). They identified that 0.5% NaOH treatment improved the interfacial bonding and wettability of the fibre compared with seawater treatment because the alkaline treatment dissolved certain amount of lignin and hemicellulose and removed wax, oils and impurities (El-Shekeil et al. 2012).

Mechanical properties of SPF biocomposites

Several researchers and scientists have documented reviews on SPFs and their properties (Sahari et al. 2012a; Ishak et al. 2013). However, these articles provide limited facts on the mechanical performance of SPF-reinforced polymer biocomposites until 2017 (Mukhtar et al. 2016; Sanyang et al. 2016a; Huzaifah et al. 2017). Thus, the present review covers more comprehensive information on the mechanical properties of sugar palm biocomposites and recent works on the mechanical behaviour of SPF biocomposites with up-to-date data until 2021. Table 6 demonstrates the latest works conducted by various researchers on SPF-reinforced polymer biocomposites.

SPF-reinforced thermoset polymer composites

Various studies have been conducted on sugar palm-reinforced thermoset polymer biocomposites. A team of researchers led by Ammar et al. (2019) demonstrated that fibre arrangement plays vital roles in the mechanical performance of SPF-reinforced vinyl ester (VE) biocomposites. They indicated that the flexural strength and stiffness of unidirectional fibre composites showed the highest values compared with ± 45° and 0/90° woven fibre composites. Unidirectional SPF-reinforced VE biocomposites were fabricated through a hand lay-up technique, showing high bending strength due to tension and compression loads from flexural load aligned with the direction of fibres. Figure 5 shows the flaws, such as rupture matrix and vacant slots, of ± 45° woven fibre VE composites.

Huzaifah et al. (2019a) demonstrated that the high fibre loading of SPFs in a sugar palm/VE biocomposite resulted in decreased flexural and tensile properties. From their result, 30 wt% SPF loading showed the highest impact strength compared with other composition because the fibre loading was sufficient to absorb impact energy. Table 7 displays the influence of fibre weight on the impact properties of SPF-reinforced VE biocomposites. Huzaifah et al. (2019b) discovered that a long soil burial period reduced the flexural, impact and tensile impact strengths of composites. The decrease in mechanical strength might be due to that the fibre induced wettability caused by moisture absorption and the poor interfacial adhesion of fibre/matrix.

Moreover, numerous studies have evaluated the effect of treated SPFs on its thermoset biocomposites. Bachtiar et al. (2009, 2010a) observed that epoxy reinforced by treated SPFs improved the flexural and impact strengths by approximately 24.41% and 12.85% of those of untreated fibre composites, respectively. The strong adhesion at the interface of the fibres via chemical treatments contributed enhanced permeability, which inhibited detachment, debonding or pull-out of fibres (Bledzki et al. 2009; Amir et al. 2019).

An investigation has elaborated that 30 wt% of fibre loading with unidirectional fibre is sufficient for a sugar palm/UPE biocomposite (Nurazzi et al. 2020) having tensile properties favourably similar to those of the most widely used 50 wt% fibre of unidirectional flax-reinforced UPE composites prepared using the same compression moulding technique (Marais et al. 2005).

Many experiments have been performed on sugar palm-reinforced thermosets biocomposites in different modification, including inclusion of additive particles and physical and chemical treatments of SPFs. Incorporation of additives, such as silica aerogel and nanoclay powders, would compatibilise the polymer matrix and the cellulosic fibre to allow good adhesion, increase the activation surface area, decrease the length of fibre breakage and pull-out, and increase the degree of roughness in the matrix (Avella et al. 2008). For instance, Shahroze et al. (2018) studied the impact of nanoclay addition on the mechanical properties of SPF/UPE biocomposites. They concluded

Table 6 Reports on mechanical properties of sugar palm biocomposites

Fibre	Fibre condition	Matrix	Matrix type	Treatments/ Conditioning	Flexural		Tensile		Impact	References
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/m^2)	
Sugar palm	10 wt% (long fibre)	Vinyl ester	Thermo-set	–	93.08	3328	15.41	2501	–	Ammar et al. (2019)
		Epoxy		0.5M of NaOH at 8hrs	90.68	4672	41.88	3780	6.0	Bachtiar et al. (2008, 2009, 2010a)
		Vinyl ester		–	48.5	2294.2	25.1	2588	4.5	Huzaifah et al. (2019a)
				200 hrs of soil burial	18.01	–	14.22	–	8.87	Huzaifah et al. (2019b)
	30 wt% (powder fibre)	Phenolic		0.5% of NaOH at 4 hrs	92.59	5.17	–	–	7.28	Rashid et al. (2017b)
	30 wt% (long fibre)	Epoxy		Seawater 30 days	54.22	–	–	–	18.46	Ishak et al. (2009)
	-	Unsaturated polyester		4% of nano-clay	68.12	3.788	21.91	3.683	6.919	Shahroze et al. (2018)
	30 wt% (mat fibre)	Unsaturated polyester		3% of silica aerogel	56.6	3.00	19.7	3.5	68.3	Shahroze et al. (2019)
	30 wt% (long fibre with 15 cm fibre length)	Unsaturated polyester		Seawater for 30 days	80.80	–	18.33	4.252	–	Maisara et al. (2019)
				–	97.5	6.9	42.00	4.43	–	Nurazzi et al. (2020)
	30wt% (mat fibre)	Poly-propylene	Thermo-plastics	10wt% of sodium bicarbonate solution for 5 days	60	2.47	58.76	2.06	17.61	Mukhtar et al. (2019)
	30wt% (powder fibre)	Poly-propylene		2 wt% of silane for 3 h	–	–	23.00	1.096	–	Zahari et al. (2015)
	30 wt% (Short fibre)	PVDF		–	52.49	2.151	23.06	2.243	–	Alaaeddin et al. (2019)
	30 wt% (Long fibre)	HIPS		4% of NaOH	–	–	32.94	1.354	–	Bachtiar et al. (2011a, b)
					–	–	28.91	0.760	–	

Table 6 (continued)

Fibre	Fibre condition	Matrix	Matrix type	Treatments/ Conditioning	Flexural		Tensile		Impact	References
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/ m^2)	
	30 wt% (Short fibre)	Polyurethane		4% of NaOH and 70°C microwave treatment	–	–	18.42	1.307	–	Mohammed et al. (2018)
	30 wt% (Short fibre)	PVB		30% of seaweed	–	–	1.59	0.73	–	Syaqira et al. (2020)
	- (long fibre)	Polyurethane		2 wt% of silane for 3 h	–	–	173.44	10.07	–	Atiqah et al. (2018a)
	- (long fibre)	Polyurethane		6 wt% NaOH and 2 wt% of silane for 3 h each	–	–	142.09	7.75	–	Atiqah et al. (2018a)
	10 wt% (Short fibre)	PLA	Bio-polymer	0.25% of NaOH	–	–	32.5	0.263	–	Chalid and Prabowo (2015)
	–	SP starch/agar		30% of seaweed	32.5	3.00	22.0	3.250	5.5	Jumaidin et al. (2017a)
	30 wt% (Short fibre)	Sugar palm starch		72 h immersed in water	–	–	1.75	–	9.0	Sahari et al. (2013)
	0.5 wt% (Nano crystalline fibre)	Sugar palm starch/PLA		20% of SP starch loading	35.38	2.38	19.45	1.19	–	Nazrin et al. (2020)

HIPS High impact polystyrene, *PVDF* Polyvinylidene Fluoride, *PVB* Polyvinyl Butyral; PLA Poly(latic) Acid, *NaOH* Sodium hydroxide solution

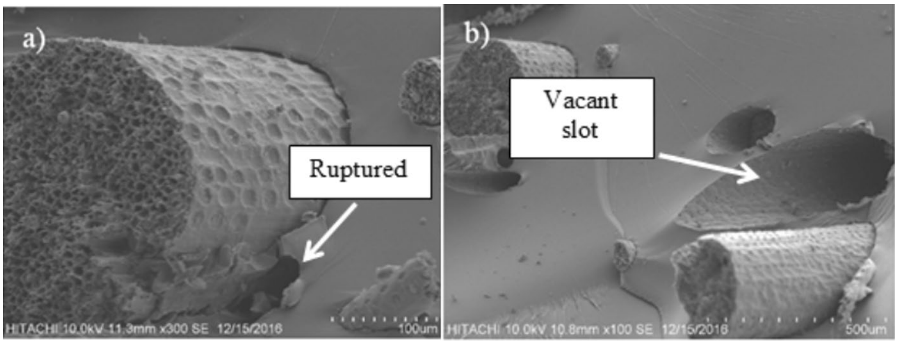

Fig. 5 SEM of ± 45° woven fibre VE composites showing **a** ruptured matrix; and **b** vacant slots (Ammar et al. 2019). Creative Common CC BY license

Table 7 Influence of fibre weightage on the tensile properties of SPF reinforced VE biocomposites (Huzaifah et al. 2019a)

Fibre loading (%)	Impact strength (kJ/m^2)	Flexural strength (MPa)	Tensile strength (MPa)
10	4.5	48.5	25.1
20	4.5	24.0	12.5
30	5.9	18.8	9.7
40	5.4	2.5	6.1

that the addition of nanoclay to SPF-reinforced UPE biocomposites improved the mechanical properties, and 2 wt% NC had the best flexural and impact strengths. The addition of the nanoclay filler, which filled up micropores, enhanced the topological surface of the composites. Shahroze et al. (2019) incorporated another additive, namely, silica aerogel, into SPF/UPE biocomposites and evaluated their mechanical performance. They found that 3 wt% silica aerogel in 30 wt% SPF-reinforced 70 wt% UPE biocomposites exhibit the highest tensile, flexural, and impact properties. This finding shows that the addition of nanoclays and silica aerogel with optimum concentration can improve the mechanical performance of sugar palm biocomposites. In this case, the inclusion of 30 wt% silica aerogel in the SPF reinforced UPE composites reduces fibre pull out because it has higher degree of surface roughness as shown in Fig. 6. Subsequently, the higher degree of surface roughness would contribute to better mechanical performance at optimum silica aerogel content in the SPF-reinforced UPE composites. Thus, it can be concluded that incorporation of additives promotes the sugar palm biocomposites to be implemented in engineering fields, such as automotive components, aerospace and structural applications.

SPF-reinforced thermoplastic polymer composites

The research interest on sugar palm biocomposites is growing day by day. A researcher has studied the effect of fibre size and loading on the tensile properties and moisture absorption of sugar palm–polyvinyl butyral (Syaqira et al. 2020). A short sugar palm biocomposite (30 wt%) exhibited the best performance in terms of tensile performance and water uptake rate. Alaaeddin et al. (2019) determined that the use of short fibre led to adequate interfacial bonding between SPFs and polyvinylidene fluoride matrix. Short fibre composites exhibited outstanding compatibility, strength and a homogenous structure in the fibre/matrix. They also had good physical properties and excellent resistance to water absorption, moisture content and thickness swelling.

Zahari et al. (2015) shows that the silane-treated SPFs in a polypropylene (PP) thermoplastic matrix recorded high tensile strength and modulus of 23 MPa and 1.098 GPa, respectively. The study shows that 30 wt% SPFs is the optimum loading value to a reinforced thermoplastic polymer matrix, and silane treatment allows the fibre to have enhanced adhesion properties within the matrix. Figure 7a–c show that the untreated SPF/PP composites exhibit poor adhesion between the SPFs and PP matrix. However, the gaps were remarkably less obvious and become narrower because the SPFs were treated with silane. This indicates that the SPFs and PP matrix has better compatibility when treated with silane solution which subsequently increased the strength of the sugar palm biocomposite. Additionally, the higher fibre content with silane treatment allows better stiffness of the composites because the treatment allows better SPF distribution within the PP matrix (Ichazo et al. 2001).

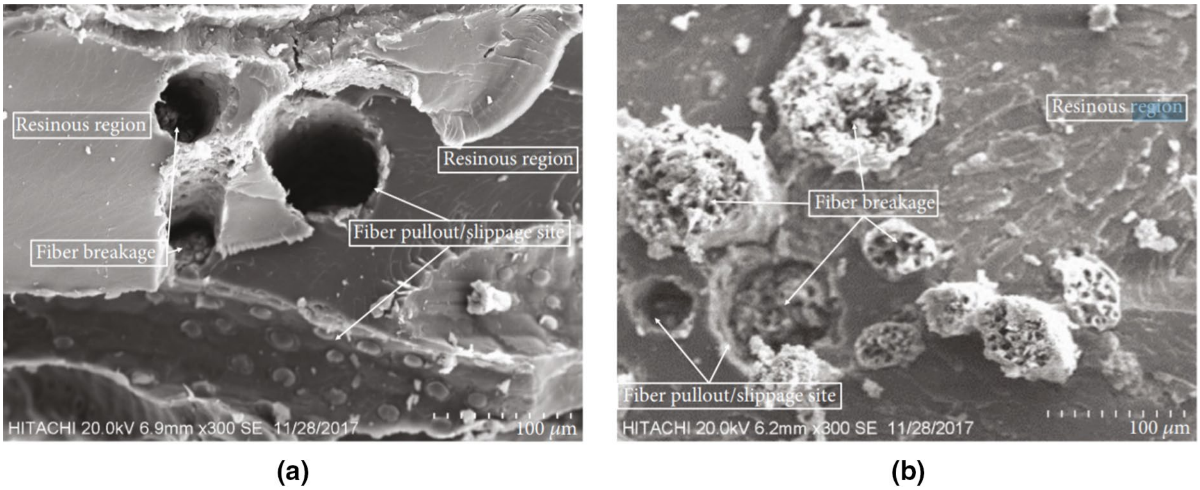

Fig. 6 SEM morphological analysis of SPF/PE **a** without silica aerogel and **b** 3% silica aerogel-infused SFP/UPE biocomposite (Shahroze et al. 2019). Creative Common CC BY license

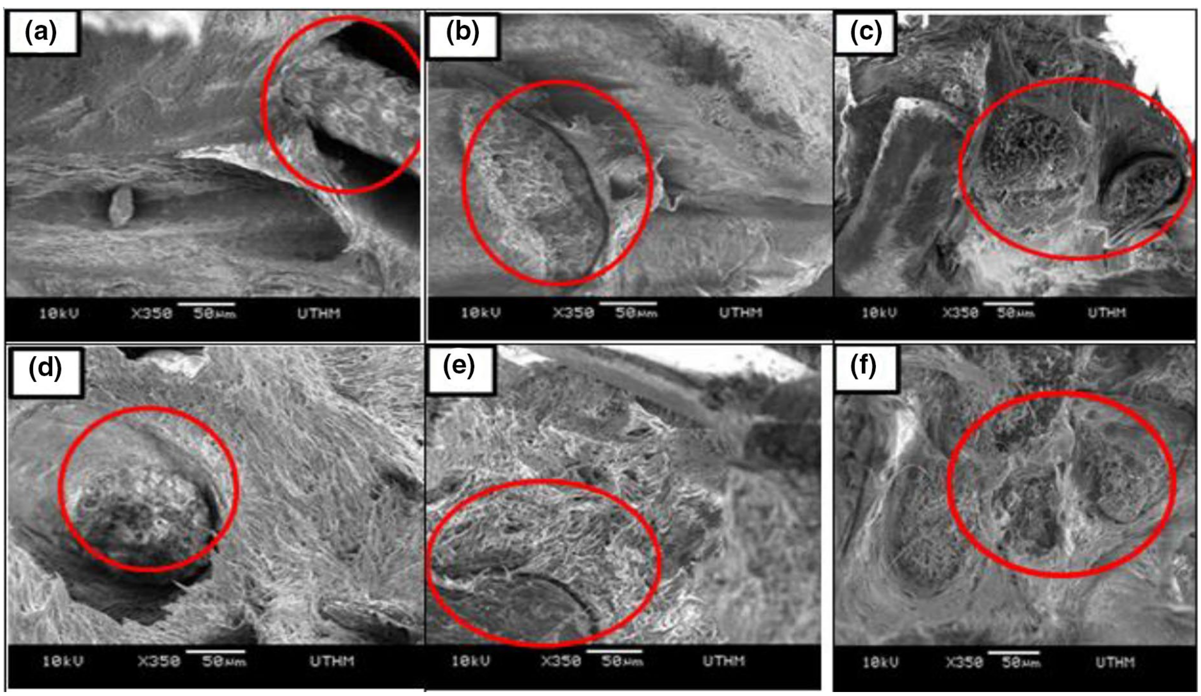

Fig. 7 SEM morphology of **a** untreated SPF/PP composites at 10wt%, **b** untreated SPF/PP composites at 20wt%, **c** untreated SPF/PP composites at 30wt%, **d** silane treated SPF/PP composites at 10wt%, **e** silane treated SPF/PP composites at 20wt%, and **f** silane treated SPF/PP composites at 30wt% (Zahari et al. 2015). Reproduced with permission from Zahari et al. 2015. Copyright 2015 Elsevier

Some researchers have combined the aforementioned technique with fibre treatment to improve the performance of sugar palm biocomposites. The influence of mercerisation treatment and (*polysterene-block-poly(ethylene-ran-butylene)-block-poly(strene-graft-maleic-anhydride)*) compatibilising agent on mechanical performance has been studied for SPF-reinforced high-impact polystyrene (HIPS) with 40/60 blend ratio by weight (Bachtiar et al. 2011a, b). Researchers have demonstrated that the tensile strength and modulus of alkaline-treated sugar palm and HIPS biocomposites are efficiently increased compared with those using a compatibiliser agent. This result could be due to fibrillation, reduction in fibre diameter, increase in reactive sites and changes in the chemical composition of fibres (Kalia et al. 2009). Mohammed et al. (2018) elaborated that the combination of microwave and alkaline treatments offered excellent tensile properties compared with the use of alkaline-treated and -untreated sugar palm/polyurethane biocomposites. The addition of microwave treatment at 70 °C allowed the removal of the remaining wax and impurities on the lignocellulosic fibre after the removal of impurities at the outer layer of the fibre via alkali treatment. The microwave treatment would also reduce the excess moisture in the fibre and subsequently improve the interfacial adhesion of fibre/matrix (John and Anandjiwala 2008). However, microwave treatment after 70 °C does not efficiently improve composite strength because the elevated temperature may damage the fibre and reduce the amount of reactive sites within the fibre.

SPF-reinforced biopolymer composites

The tensile strength and modulus of SPF-reinforced polylactic acid (PLA) green composites have been amplified smoothly and linearly with a fibre content of 20% at 0.25 M sodium hydroxide treatment for 30 min (Chalid and Prabowo 2015). The change in SPF interface would enhance the properties of PLA composites via strengthening the mechanical interlocking with the resin. Trapped voids and fibre pull-out could also be lessened by stirring during mixing the fibre with the dissolved PLA resin (Puglia et al. 2004; Singha and Thakur 2008). Sahari et al. (2013) evaluated the effect of fibre loading and water absorption on the mechanical properties of an SPF-reinforced SPS green composite. The impact and tensile strengths of the composite shows significant increment with fibre loading up to 30%. This finding was due to the efficient stress transfer between SPFs and SPF polymer is optimum at 30% fibre loading. However, the tensile strength of the sugar palm green composite seems degraded after being exposed for 72 h in 75% relative humidity. In this point of view, it can deduced that the SPF/SPS green composites shows that SPF has a good dispersion and adhesion in SPS biopolymer.

Nazrin et al. (2020) prepared a sugar palm nanocrystalline fibre-reinforced SPS/PLA bionanocomposite through melt blending and compression moulding, as shown in Fig. 8. They discovered that the increase in starch loading resulted in decreased overall mechanical (tensile and flexural) properties of the sugar palm bionanocomposite. A high content of SPS led to agglomeration, whereas a low content resulted in the presence of cracks and voids (Sanyang et al. 2016b; Ilyas et al. 2019). Moreover, the thermal stability of the sugar palm bionanocomposite was reduced as the starch loading increased. The physical property, such as thickness swelling, corresponded to water absorption and demonstrated an increasing trend with increasing starch volume.

Jumaidin et al. (2017a) studied the influence of seaweed on the mechanical, physical and thermal properties of SPF-reinforced SPS/agar green composites. Substantial improvement in the flexural, impact and tensile behaviour of the green composites was observed due to the incorporation of seaweed. The high intermolecular hydrogen bonding in the FT-IR results implied the good compatibility between seaweed and SPS/agar. The similar hydrophilic nature of seaweed and SPS/agar aided in the improved adhesion between the filler and the matrix. Thus, *Eucheuma cottonii* seaweed waste can be used as an excellent filler in sugar palm green composites, which are useful for packaging applications.

Hybrid SPF/other fibres reinforced polymer composites

Hybrid composites are commonly prepared either by a combination of two fibres in a single matrix or by using one fibre in two polymer blends (Asyraf et al. 2020b). These hybrid composites act as a new unique material that weighs the sum of the individual components. The properties of hybrid composites are governed by the fibre/matrix interfacial bonding, fibre length, orientation, extent of intermingling of fibres, fibre content and hybrid fibre arrangement. Table 8 displays the most recent works on hybrid SPF-reinforced polymer biocomposites.

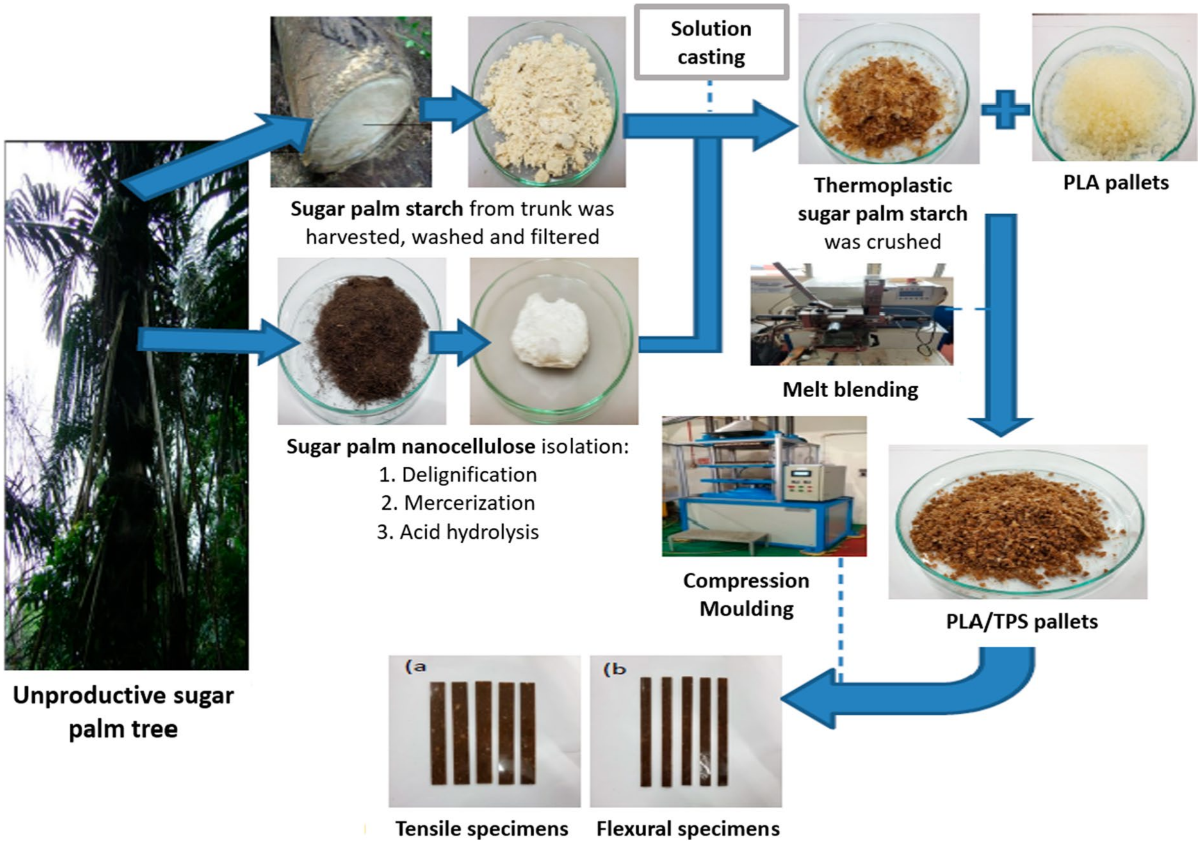

Fig. 8 Sugar palm nanocrystalline fibre reinforced sugar palm starch/PLA bionanocomposites preparation (Nazrin et al. 2020). Creative Common CC BY license

Several researchers have used hybrid sugar palm with other lignocellulosic fibre-reinforced synthetic polymer biocomposites. For instance, short sugar palm and kenaf fibres (0.1–0.5 mm size) were hybridised in polypropylene resin by researchers (Bachtiar et al. 2014) to study the pronounced influence of hybrid fibre loading on tensile properties. The tensile strength of the hybrid composites decreased as the fibre volume was elevated. Hybrid biocomposites with kenaf fibre have also displayed higher tensile strength, and the stiffness of the hybrid biocomposites was higher than that of pure resin due to the ability of the hybrid fibre to withstand shape before breaking (Srinivasan et al. 2014). Radzi et al. (2019b) used a hybrid short fibre of sugar palm and roselle to form a hybrid fibre-reinforced polyurethane biocomposite. In their findings, the hybrid composite showed improved impact properties with increasing sugar palm content. However, the tensile and flexural properties declined with the increase in sugar palm volume due to fibre pull-out and poor adhesion bonding. Siregar et al. (2020) also explored the effect of fibre layering sequence of hybrid sugar palm/ramie-reinforced epoxy biocomposites on mechanical properties. They discovered improved tensile and flexural strength performance when woven ramie existed at the outer layer of the compress moulded hybrid biocomposites.

Afzaluddin et al. (2019) fabricated a sugar palm–glass hybrid fibre-reinforced polyurethane biocomposite through a compression process and reported that high tensile and impact properties were obtained at high SPF loading in relative to glass fibre. The highest mechanical performance was recorded at the hybrid 30% of SPFs and 10% of glass fibre-reinforced in thermoplastic polyurethane (TPU) composite. Figure 9a shows that a quite strong adhesion between the SPFs and glass fibre to the TPU matrix. This result might be due to more glass fibre

Table 8 Recent works on mechanical properties of hybrid SPF biocomposites

Fibre	Hybrid fibre	Matrix	Matrix type	Treatments/ Conditioning	Flexural		Tensile		Impact	Refernces
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/ M^2)	
30 wt% of SPF (short fibre)	10 wt% of glass (chopped fibre)	Polyurethane	Thermo-plastic	–	17.5	0.25	21.5	0.7	20.6	Afzaluddin et al. (2019)
10 wt% of SPF (short fibre)	30 wt% of roselle (short fibre			–	10.19	0.16	13.6	1.0	29.4	Radzi et al. (2019b)
10 wt% of SPF (short fibre)	10 wt% of seaweed (long fibre)	SP starch/agar		–	31.25	3.25	17.74	3.95	6.0	Jumaidin et al. (2017b)
6 wt% of SPF (short fibre)	8 wt% of SP (short fibre)	Corn starch		–	–	–	19.09	1.17	–	Ibrahim et al. (2020)
18.1 wt% of SPF (short fibre)	18.1 wt% of glass (strand mat)	Unsaturated polyester	Thermo-set	–	151.34	7.28	61.69	8.12	4.9	(Sapuan et al. 2013)
10 wt% of SPF (short fibre)	20 wt% of kenaf (short fibre)	Polypropylene		–	–	–	17.00	0.64	–	Bachtiar et al. (2014)
10 wt% of SPF (long fibre)	15 wt% of ramie (woven fibre)	Epoxy		5 layer of ramie–SP–ramie–SP–ramie	80.70	4.26	52.66	8.34	–	Siregar et al. (2020)

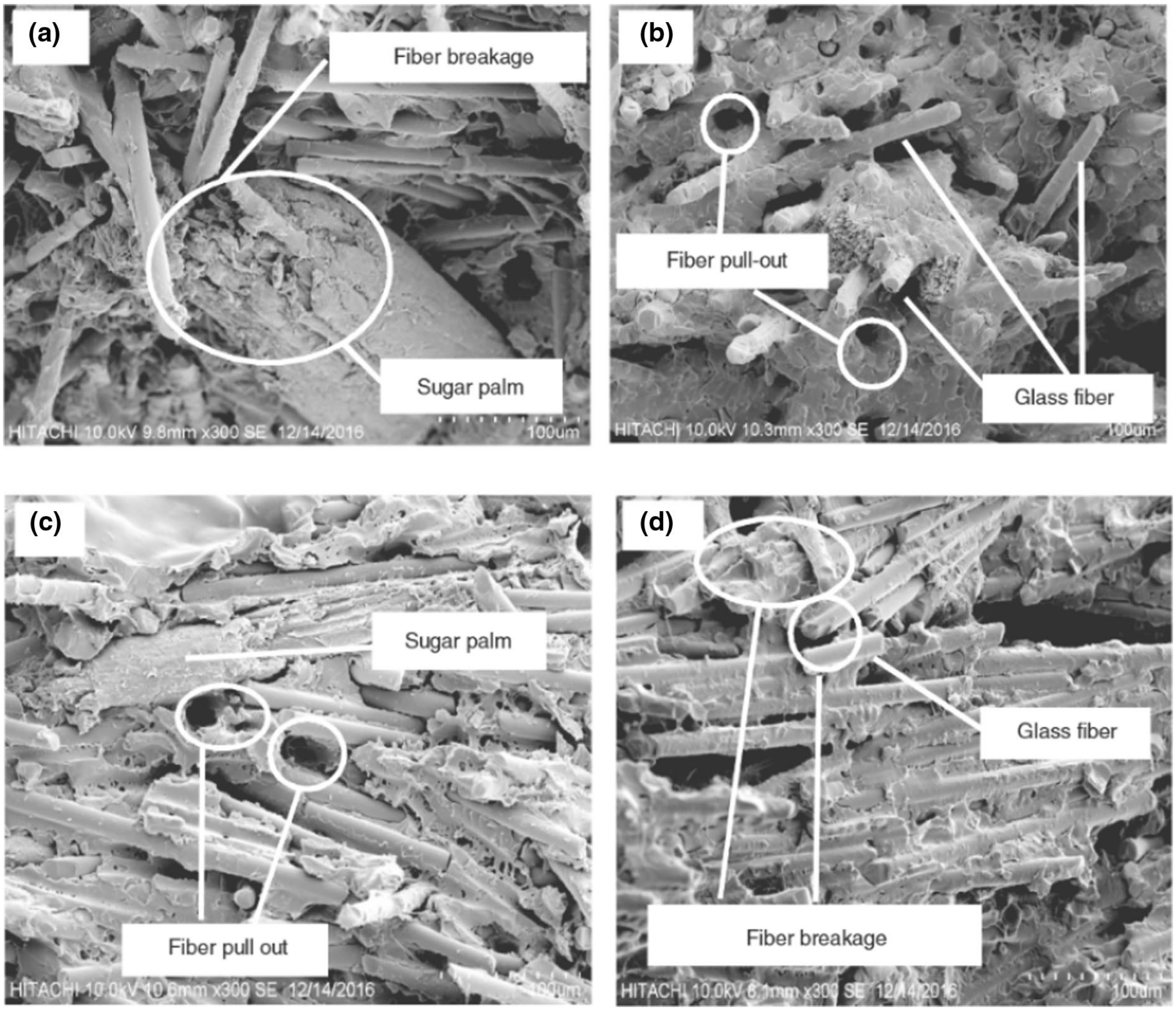

Fig. 9 SEM micrograph of cracks developed in the **a** 30/10 SPF/glass, **b** 20/20 SPF/glass, **c** 10/30 SPF/glass and **d** 0/40 SFP/glass (Afzaluddin et al. 2019). Reproduced with permission from Afzaluddin et al. 2019. Copyright 2019 Elsevier

stretching out causing another SPF breakage and pull out at the middle without any stretching as shown in Fig. 9b. Meanwhile, Fig. 9d indicates that 40 wt% glass fibre displays brittle property of glass fibre as noticed in SEM analysis. Besides that, the high fibre loading of SPFs would allow effective dispersion of the fibres and outstanding load transference occurring at this composite composition (Sapuan et al. 2013). However, the flexural strength and modulus were elevated when a higher glass fibre content was introduced at 40 wt.%. The increased glass fibre volume in the matrix improved the shearing resistance of the composite and reduced shear failure (Velmurugan and Manikandan 2007). According to Afzaluddin et al. (2019), high density, low thickness swelling and water absorption properties can be achieved with incorporation of 30 wt% glass fibre into sugar palm-reinforced polyurethane biocomposites.

A group of researchers hybridised lignocellulosic fibre-reinforced biopolymer green composites for packaging application (Ibrahim et al. 2020). They demonstrated significant improvement in the tensile modulus and strength of the green composite film following a hybridisation process at 6% SPF. This finding showed that SPFs could dominate the mobility of thermoplastic starch polymers and promote interfacial bonding by creating a network to hold the composites. This condition facilitated the stress transfer between the fibre and matrix. The same results were obtained by Jumaidin et al. (2017b) through hybridising seaweed and SPFs in starch/agar green composites, which promoted enhanced tensile and flexural properties.

Conclusion

This review paper comprehensively explains the mechanical performance of sugar palm biocomposites from previous studies. SPFs have outstanding mechanical performance, especially in terms of tensile and flexural strengths, as confirmed by several works. In this case, 30 wt% loading can be considered as the optimum loading to achieve a good mechanical behaviour in biocomposites although no certain fibre volume has been determined to enhance the mechanical properties of biocomposites. Furthermore, this review also provides information for further research on the mechanical behaviour of sugar palm biocomposites especially for engineering applications. Variations in the mechanical properties of sugar palm-reinforced thermoplastic and thermoset biocomposites have been reported by several researchers. Overall, sugar palm-reinforced UPE biocomposites demonstrate better mechanical performance than other polymer matrices. In addition, SPFs have great potential to replace synthetic fibres for bending, tensional, and impact force applications. Thus, the utilisation of SPFs in hybrid biocomposites has great potential in the construction, structural, and housing sectors.

Sugar palm reinforced green composites can be used in many applications such as housing materials due to their light weight, great strength and insulation, and effective fireproof properties. Therefore, future research should consider the development of construction and structural products, such as cross-arm beams, by using hybrid SPFs along with high-performance biodegradable resin with enhanced mechanical properties. Thus, the SPFs can potentially be a protruding contender in advanced material applications.

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Declarations

Human and animals rights No animal study or human participant involvement in the study.

Conflict of interest The authors declare that they have no conflict of interest.

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