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Review Article

Mechanical properties of oil palm fibre-reinforced polymer composites: a review

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ABSTRACT

In recent years, serious reduction in petroleum resources and concerns about the usage of synthetic plastics have prompted global communities to accept the use of natural fibres and biopolymers in many products. Lignocellulosic fibre polymer biocomposites have attracted the attention of scientists and engineers because of their wide availability, low carbon emission and biodegradability. Currently, oil palm is one of the main crops

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cultivated in Malaysia and Indonesia and is regarded as a potential source of lignocellulosic fibres for biocomposites. The cellulosic content of oil palm fibres (OPFs) enhances the mechanical properties of composites. Ensuring the compatibility of OPFs as main constituents with other materials in composites for a specific applications is essential. Mechanical performance in terms of tensile, flexural and impact strength determines an OPF's compatibility. However, no comprehensive reviews focusing on the mechanical properties of OPF biocomposites have been published, and factors influencing mechanical performance, such as interfacial adhesion, stacking sequence, additive, type of polymer and fibre size have not been explored. Some studies have identified the research gaps and deduced that the potential applications of OPFs as reinforcement materials in composites have not been explored.

1. Introduction

Oil palm is one of the major economic crops in numerous countries, and oil palm plantation areas have expanded around the world. Oil palm is an important agricultural crop in Malaysia, which is the fourth largest contributor to the country's gross national income [1,2]. Malaysia produces millions of tonnes of oil palm fibres (OPFs) each year [3]. OPFs from mills consist of oil palm empty fruit bunch (OPEFB), oil palm mesocarp fibre (OPMF) and palm kernel shell and palm oil mill effluent. In plantation areas, OPFs are regularly cut during the harvesting of fresh fruit bunches and pruning of palm trees and collected [4].

OPMF is utilised as fuel for steam boilers in mills. However, it is used inefficiently because of its large amount. OPEFB is usually inexhaustible and only 10% can be used for other purposes [5]. Meanwhile, OPF is felled in between the inter-rows of oil palm plants because, once decomposed, it is reused as a fertilizer containing high amounts of nutrients [2]. Biomass generated from oil palm industries has attracted great interest from researchers because it is abundant and can be converted into value-added materials, such as bioplastic, biosugars, nanocellulose, electricity, biogas, biohydrogen, adsorbents and polymer composites [6–15].

Recently, research on the replacement of man-made fibres with natural fibres as reinforcement materials in polymer composites has increased dramatically. Natural fibres have the advantages having low densities and low prices and being non-toxic and environmentally friendly. Additionally, they are available in large amounts and renewable. Moreover, they cause a low degree of equipment abrasion and are simple in processing. Cellulosic fibres, such as sisal, jute, hemp, coir, bamboo, wood, banana, oil palm and kenaf are used as reinforcement materials for composites [15–17]. OPF-based composites have potential uses in structural and non-structural applications, such as automotive, biomedical, military, adsorbent, floor panel, furniture and household products [18–22].

OPF is a promising material for polymer composite production. Fibre-reinforced polymer composites or bicomposites are used in many products and applications. Many reviews have discussed the potential uses of natural fibre-reinforced polymer composites in construction and building applications because of its mechanical performance. These natural fibres include flax [23], sisal [24] and kenaf [25,26] fibres, which exhibit remarkable mechanical properties. OPF can be used in various composite applications because of its strength and ability to reinforce polymer matrices. The biomass of OPF obtained from fruit bunch, frond and mesocarp is usually burned in open fire. Owing to environmental concerns, the by-products are somehow transformed to pulp and paper, bio-organic compost and block board production [27]. The Malaysian government has initiated efforts to explore new markets for oil palm biomass, and numerous composite studies have been conducted to explore the prospective industrial applications of OPF-reinforced polymer composites [28,29]. One example in general composite application is the use of oil palm trunk fibres as concrete reinforcement [30].

The porous surface morphology of OPF facilitates mechanical interlocking with matrix resin in composite fabrication. OPFs are suitable for composite applications because of its high cellulose content and high mechanical and crystallinity. The components of natural fibre are cellulose and hemicellulose, which contain large amounts of hydroxyl

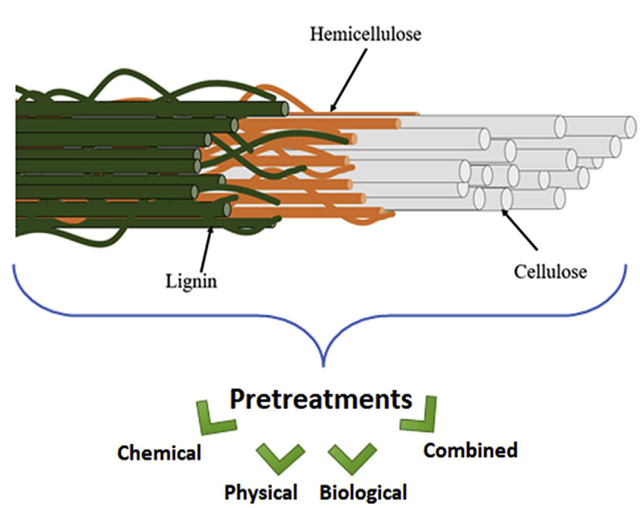

Fig. 1 – Overview of the complex structure of lignocellulosic fibre and treatments [11].

groups. The presence of hydroxyl groups makes the fibres hydrophilic, causing poor interfacial adhesion with hydrophobic polymer matrices [27,31] and the poor physical and mechanical properties of composites. Moreover, using natural fibres has many drawbacks. OPFs for composite production have poor compatibility with polymers, low thermal degradation and high water absorption capacities. Thus, fibre surface modification is necessary. The removal of hemicellulose can reduce the hydrophilicity of fibres [32,33]. The surface modification of natural fibres is aimed at hemicellulose removal and can be used in improving interfacial adhesion between fibres and polymer matrices. Figure 1 shows the structure of lignocellulosic fibres and pre-treatments.

In recent years, physical and chemical treatments or their combinations have been used in decreasing the hydrophilicity of OPFs. These methods have been extensively studied [34,35]. Chemical treatment is widely used in manufacturing composites because of its effectiveness [36]. Among the chemical treatments, alkalisation is one of the most economical chemical treatments for natural fibres. It removes non-cellulosic substances, such as impurities, waxes, pectin and hemicellulose, which cover cellulose fibres and bind fibrils together. The removal of these substances results in rough a fibre surface and promotes surface contact. The effects promote mechanical interlocking between polymers and fibres, thus enhancing mechanical properties. Physical treatments, such as hydrothermal treatment [37], have been used in modifying fibre surfaces, improving compatibility between fibres and polymer matrices and removing hemicellulose components.

Many researchers have discussed the overall perspective of OPF and its composites, particularly Shiroj et al. [27] and Zuhri et al. [38]. Many reviews have focused on specific OPFs, such as empty fruit bunch, which is used as a reinforcement material in polymer composites [39,40]. Additionally, most reviews on OPEFB fibre biocomposites have focused on energy absorption [41,42], structural [40] and furniture design [43] applications. None of the reviews have discussed the mechanical properties of OPF-reinforced polymer composites under various composite conditions.

Thus, in this review, recent achievements in exploring the mechanical performance of oil palm-based lignocellulosic fibre-reinforced polymer biocomposites was evaluated. The review covered various types of synthetic and bio-based thermoplastics and thermoset polymers. Moreover, factors affecting the mechanical performance of the composites were explored, such as fibre loading, orientation, treatment, hybridisation with other fibre and stacking sequence. At the end of this review, potential applications and insights into oil palm fibre-reinforced polymer composites were highlighted.

2. Oil palm: background, current applications and commercial products

Oil palm (*Elaeis guineensis* Jacq.) originated from the tropical rain forest region of West Africa as shown in Fig. 2(a). It is a tropical and perennial crop grown primarily for its vegetable oil, which comprises palm and kernel oil. Palm oil is derived from mesocarp, whereas kernel oil is derived from the kernel. Fig. 2(b) and (c) display the mesocarp of palm oil fruit obtained from oil palm fruit bunch. Oil palm grows 10° north and south of the equator and is an important source of basic nutrition of natives in the equatorial regions in Africa [44]. Palm fruit is transported to the Americas and then to the Far East between the 14th and 17th centuries. The plant seems to have grown better in the Far East, showing the highest commercial yield far from its origin [45]. The palm oil sectors in Malaysia and Indonesia are based on seedlings, and the progenies have been widely dispersed since 1853 [44].

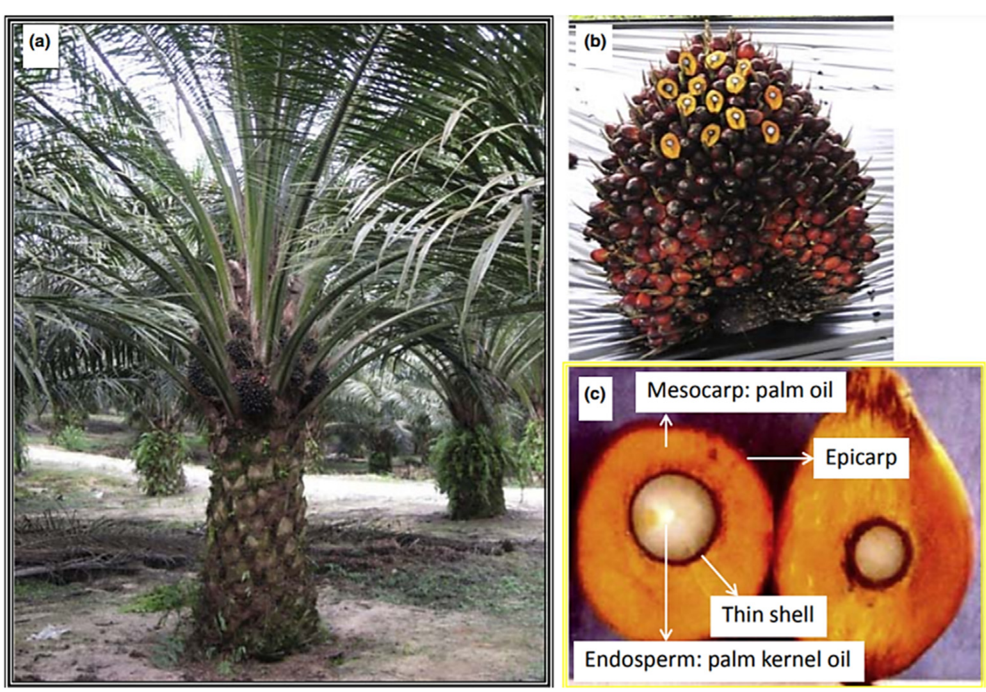

Fig. 2 – (a) Oil palm tree, (b) oil palm bunch and (c) cross-section of oil palm fruit [44].

Scanes [46] mentioned that palm oil contributes to 32% of the worldwide supply of fats and oils, and the driving force behind its growth is palm oil production efficiency in comparison with other vegetable oil sources, such as rapeseed and soybean. Palm oil is produced on over 14.2 million hectares (35.1 million acres) of plantations around the world as compared with 258.9 million hectares of land for agriculture. Plantations are mainly found in Malaysia and Indonesia, accounting for 71% of agricultural land. Thus, Malaysia and Indonesia are the leading producers of palm oil. In terms of exports, Khosla [47] stated that palm oil and palm kernel oil contribute to over 60% of global exports. Over the last four decades, palm oil has experienced rapid and consistent progress in the worldwide market, and the average annual production of palm oil in Malaysia is projected to reach 15.4 million tones between 2016 and 2020 [48].

Oil palm is the most valuable crop in Malaysia and has contributed to the country's agricultural and economic transformation. Godswill et al. [49] explored products obtained from oil palm in plantations and mills, particularly food, oleo chemicals, medical and health products and household and industrial products. The processing of fresh fruit bunch (FFB) yields crude palm oil (CPO) from the mesocarp, palm kernel oil from the seed and organic byproducts and wastes. Approximately 80% of CPO is consumed in the food sector, whereas palm kernel oil is mostly used in the oleo chemical industry. Refined CPO alone or in combination with other oils, such as cooking oil, salad oil, margarine and spread, is used in making soaps and livestock feeds. Kernal and sludge cakes, as well as wastes from palm and kernel oil extraction process, are utilised as animal feed. The fractionation of refined oil yields olein, stearin, fatty acids, alcohols and intermediary substance that are marketed and used in the food and oleo chemical sectors. Moreover, the refined oil palm also can be used as margarine and does not produce harmful trans fatty acids when consumed directly (i.e. without hydrogenation). Secondary and waste products from the palm oil industry include palm wine extracted from the top of felled trees and carotene from CPO, which can be processed into both vitamin A supplement and a natural snack food dye. Tocopherols and tocotrienols are derived from palm oil for commercial vitamin E production. CPO acts as an antioxidant in the form of carotene and tocopherol or tocotrienol that have anti-cancer properties.

Lignocellulosic biomass generated from oil palm comprises oil palm trunk (OPT), empty fruit bunch (EFB), fronds, palm-pressed fibre and shells, which are potential biomaterials. However, they are currently underutilised. Table 1 lists the proportions of products or wastes from each FFB. Hence, maximising the potential use of wastes has desirable economic and environmental benefits. An optimal solution for utilising oil palm wastes can be achieved by balancing technological, economic, energy and environmental factors [48]. OPFs are versatile and stable. They can be converted into a variety of dimensional grades for vairous purposes, such as soil stabilisation, paper manufacturing, composting and fertiliser production. Palm fibres can be utilised as fillers in thermoplastics and thermoset composites, which have many uses.

OPF is a well-known lignocellulosic fibre with a high cellulose content [51] and high toughness [52]. It can be used in composites. Oil palm biocomposites prepared using thermoset and thermoplastic polymers show good mechanical, physical, electrical, thermal and biodegradation characteristics [38,53–55]. Many studies focused on the properties of biocomposites under different loading conditions, such as tensile [56], compression [21], impact [57], flexural [58] and static [21] to evaluate the structural and load-bearing applications of the composites. The biocomposites were found to be suitable materials for indoor panels, engine covers, seat panels and door panels for automotive, locomotive and aircraft applications [21]. Research on creep and stress relaxation properties for long-term mechanical performance and the dimensional stability of load-bearing composite structures have been suggested [59,60]. The potential of OPF as a reinforcement and filler material in composites has been emphasized. Indeed, OPF can replace can replace calcium carbonate as a filler [61] and glass fibre as a fibre reinforcement [60,62,63] in composite cross arms for transmission tower applications. Additionally, the use of natural fibre composites as replacement materials for glass fibre-reinforced polymer composites for cross arm beams ensures environmental sustainability [17,64,65]. Other potential applications of oil palm biocomposites in packaging, building industry and waste water treatment sectors can be further explored. Tests, such as water absorption and swelling behaviour have been conducted [66,67]. The suitability of the electrical properties of the composites for electrical insulators and electronic and electrical components have been examined [68]. Biodegradation analysis on oil palm biocomposites as composites is essential, and their resistance to fungal attack should be evaluated before they can be used in outdoor applications [69].

3. OPF

Oil Palm Fibre (OPF) are commonly obtained from many parts of the tree, including the leaf, EFB, frond and trunk, as shown in Fig. 3. Its fundamental properties depend on the post processing technique and location of the fibre harvested. In general, the properties of the OPF can influence the final composite products with desired properties for specific applications. This information is important to the selection of appropriate industrial processes producing quality products [70].

Table 1 – Distribution of products/wastes from fresh fruit bunch (FFB) [50].

Products/Wastes	Percentage by weight to FFB (dry basis)
Palm oil	21
Palm kernel	7
Fibres	15
Shell	6
EFB	23
Palm oil mill effluent (POME)	28
Total	100

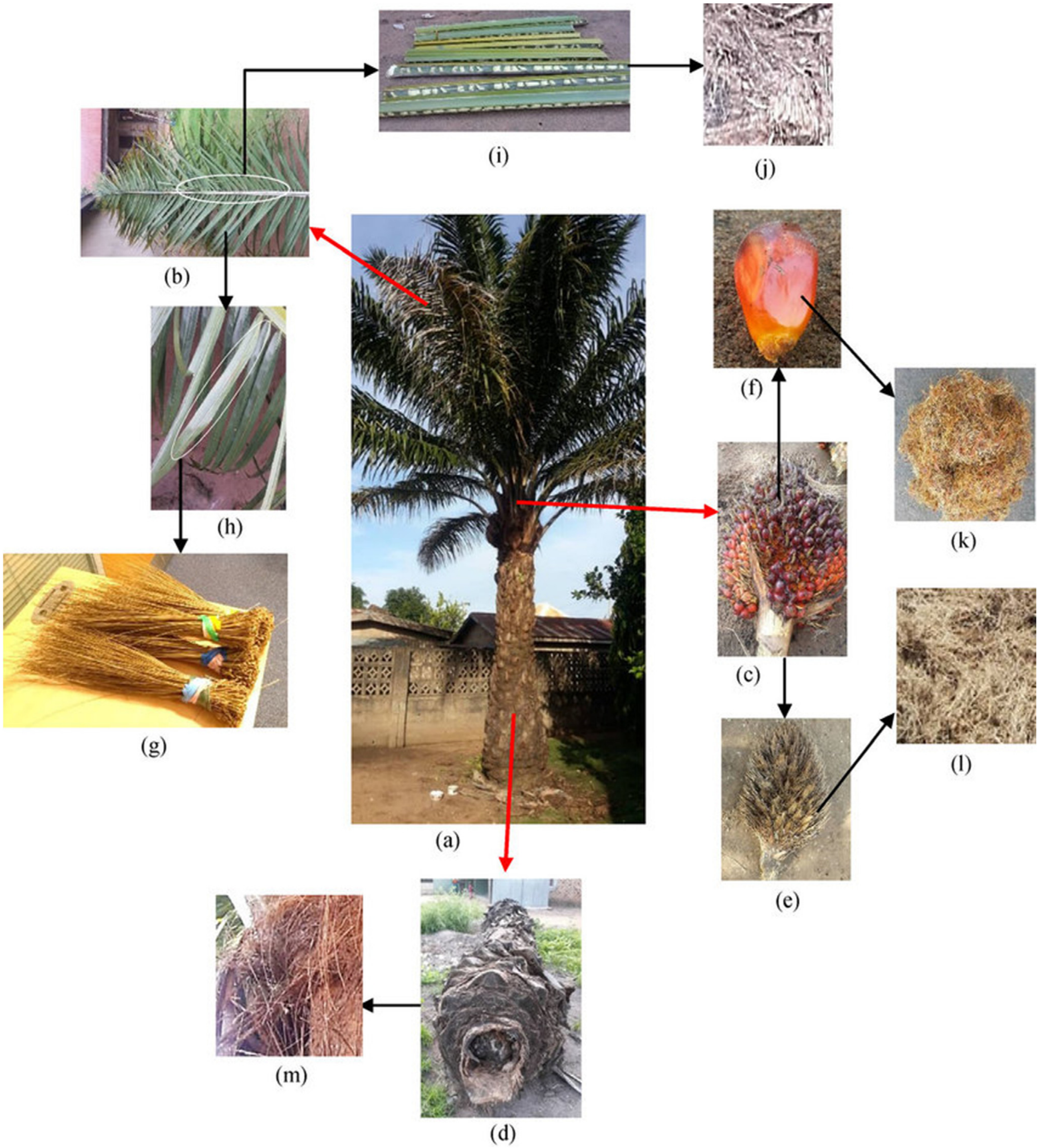

Fig. 3 – Various types of OPFs, such as (a) oil palm tree; (b) leaf; (c) fruit; (d) trunk; (e) EFB; (f) dissected fruit; (g) broom fibres; (h) leaflet; (i) oil palm frond; (j) frond fibres; (k) mesocarp fibres; (l) empty fruit bunch fibres; (m) trunk fibres (OPTF) [71].

3.1. *Categories of OPF*

Practically, OPFs are categorised according to the type of source: oil palm shell, EFB, trunk, frond and mesocarp fibres [72]. Oil palm broom fibres was mentioned for first time in the work of Momoh and Dahunsi [73]. The fibres were used to reinforce laterite-based roof tiles. EFB fibre is the most commonly used type in the development of composite products because it is abundant and cheap [74]. OPEFB fibres are extracted with a retting technique from fruit, whereas oil palm mesocarp fibres are obtained from waste materials disposed after extraction. Another well-known OPF is mesocarp fibre. Mesocarp fibres are usually palm-pressed fibre. Fibres are obtained from the biomass residue during the

Table 2 – Comparison of chemical composition of OPFs with other natural fibres.

Fibre	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Location	Ref.
Oil palm fond	25.2	49.8	20.5	Malaysia	[79]
Oil palm empty fruit bunch	22	48	25	Malaysia	[80]
	17.1	47.9	24.9	Malaysia	[81]
	–	65	19	India	[82]
Sugar Palm	7.24	43.88	33.24	Malaysia	[83]
Bagasse	19–24	32–34	25–32	India	[84]
Jute	12–20	51–84	5–13	–	[85]
Kenaf	22	44–87	15–19	Malaysia	
Coir	0.15–0.25	32–43	40–45	Malaysia	[86]

harvesting of oil through the pressing of palm fruit. Approximately 11% of OPMF is produced from palm fruit after oil extraction [75]. In general, the OPMF consists of fruit fibres, crushed kernels and shells.

Similar to the structures of most natural fibres, the fibre structures of OPFs are composed of cellulose and hemicellulose, which reinforce the lignin matrix. Therefore, OPF can be referred as a lignocellulosic fibre. The other chemical constituents of oil palm fibres include cellulose, hollocellulose and ash [76]. Hence, the present review article elaborated recent progress on research on the mechanical properties of OPF-reinforced polymer composites.

3.2. *Chemical composition of OPF*

Each cell wall structure and content depend on species and part of plants where they are harvested [77]. The three main components of the OPFs may vary (Table 2), and other natural fibres are affected by growth, soil conditions, plant age and climate influences. As the chemistry of the lignocellulosic fibres depends on plant habitat, it changes during the course of growth [78]. The tensile, flexural and rigidity properties of OPFs are influenced by the alignment of cellulose fibrils, which are generally arranged along the fibre length [15]. Table 2 shows that lignocellulosic fibres are composed of 30%–60% cellulose, 20%–40% hemicellulose and 15%–25% lignin components. In addition, the OPFs display high cellulose content compared with other natural fibres and thus potentially have high tensile properties.

Table 3 – Physical dimensions of oil palm and other natural fibres [39].

Fibres	Diameter, D (mm)	Length, L (mm)	Aspect ratio (L/D)
OPEFB	0.300	–	–
OPF (long)	0.358	142.3	397.5
OPF (short)	0.1515	17.5	115.5
Pineapple leaf	0.05	50	1000
Ramie	0.034	50	1470
Banana	0.15	45	300
Sisal	0.205	50	244
Jute	0.100	50	500
Flax	0.019	50	2631
Coconut	0.397	50	126
Bagasse	0.399	50	125
Hemp	0.031	50	1612

From the chemical point of view, cellulosic fibrils form in parallel with each other in crystalline structures and some amorphous regions. In some case, the cell wall of an OPF is derived from two main walls. This layer contain cellulose fibrils with different orientations [87]. This observation demonstrated the similarity between the structures of oil palm and coir fibres [79]. OPFs usually have tough and strong physical properties that are analogous to those of coir fibres. These amorphous and crystalline forms of OPF's cell structure contribute significantly to the determination of the mechanical performance of final composite products. The crystalline region exhibits maximum value for a composite's stiffness [88]. Numerous studies have been conducted to study the morphological and physical properties of OPFs [79,89]. The results have indicated that the mechanical characteristics of OPF-reinforced polymer biocomposites should be further explored because the mechanical performance of the biocomposites highly depend on the interactions between external variables and intrinsic structural parameters at macromolecular, molecular and microscopic levels [90].

Cellulose, hemicelluloses, lignin, sugars and starch proteins where in form three-dimensional biopolymer structures of lignocellulosic fibres. The chemical composition of the fibres plays a role in determining their performance [91]. For instance, the mechanical behaviour of the fibres highly depend on the orientation of microfibrils orientation to the cell axis. Melelli et al. [92] showed that the microfibril angle is one of the key factors for determining the stiffness of a lignocellulosic fibre. In general, microfibrils are composed of cellulose with a three-dimensional arrangement [93]. Apart from cellulose, hemicellulose components influence biodegradation, thermal degradation and micro-absorption [16,94]. Hence, collecting the data of natural fibres, especially OPF, in terms of the relationships of the chemical components with other properties is essential. These data can provide a good reference for the selection of natural fibres with specific applications [95,96].

3.3. *Physical and structural properties of OPF*

According to Facca et al. [97], the regulation of the properties of biocomposites containing natural fibres, such as OPFs, depend on the aspect ratio of length (L) and diameter (D). From this point of view, the aspect ratio L/D reflects the total surface

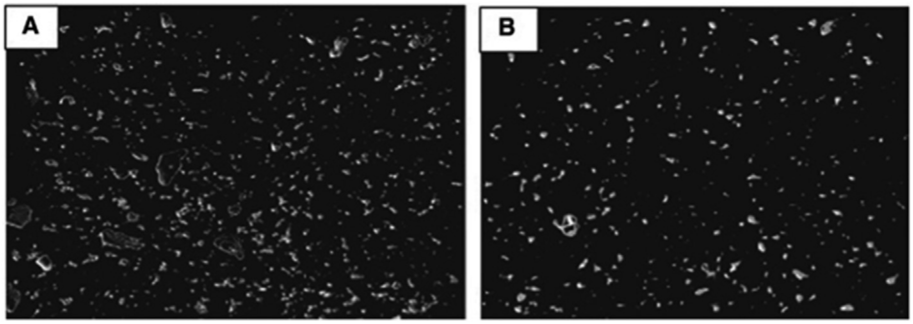

Fig. 4 – X-ray computed tomography images of jute–PLA composite: (A) long jute fibre. (B) short jute fibre [102].

area of a lignocellulosic fibre applied to reinforce a polymer matrix and affects the interfacial adhesion bonding between fibre and the matrix. Nevertheless, the failure of a biocomposite is highly influenced by the fibre size and cross-section of the lignocellulosic fibre, which is not uniform along the fibre length [98]. These properties may result in an undesirable final composite laminate [99–101].

OPFs are obtained from oil palm biomass in the form of thread-like bundles. In the post-processing stage, OPF are approximately 10–30 or 50–60 mm long. In general, the average fibre length is 200 μm. Yusoff et al. [56] studied that the influence of OPF length on its mechanical properties. In term of length, OPFs are classified as hardwood or softwood [81]. The length-to-diameter ratio (aspect ratio) of a fibre has significant effects on the properties of final composite materials. Table 3 displays the average diameter, length and aspect ratio of OPFs and compares them with those of other lignocellulosic fibres. The OPFs showed lower aspect ratios. In this case, the short OPFs can be used as additive fillers in polymer composites to enhance stiffness. Arao et al. [102] used long jute fibres to increase the L/D aspect ratio. However, this approach led to aggregation, as seen in the optical images shown in Fig. 4. Fig. 4(A) and (B) depict the topography image of short and long jute fibres reinforced PLA composites, respectively. In the sample with 5 wt.% fibres, the PLA matrix is not visible, and the cross-section was perpendicular to the flow longitudinal direction. No aggregation occurred in the short fibre jute–PLA composites. Thus, short fibre jute–PLA composites were used in obtaining the optimal mechanical properties of the composites in injection moulding for composite fabrication. The good dispersion of short jute fibres was achieved by compounding with a twin-screw extruder, which increased the tensile strength and stiffness of the jute–PLA composites.

4. Key issues regarding OPF and its biocomposites

According to Abdullah and Sulaiman [48], crude oil produced by pressing digested palm fruit contains varying amounts of water and fibres. The waste fibre obtained is transferred as a fuel. However, fresh OPEFB has a high moisture content, frequently exceeding 60% on a wet EFB basis. Therefore, it is a poor fuel when not dried and causes a considerable amount of emission because of the prohibition on open burning by the government. Moreover, the disposal of EFB onto an oil palm plantation without the collection of remaining oil in the EFB contributes to oil spills.

Despite the emission concern, dry lignocellulosic residues from oil palm wastes can be utilised in producing various types of value-added products, including bio-based fillers for synthetic biopolymers. The main benefit is that they provide a green method for improving mechanical properties and thermal stability while simultaneously minimising the utilisation of inorganic fillers. Natural fibre-reinforced polymer composites, which are conventional synthetic fibres and include glass and carbon, are being replaced by natural fibres, which are lightweight, sustainable, economically viable, abundant, inexpensive and biodegradable and have low density and outstanding mechanical characteristics [103]. Table 4 highlights the comparison between natural and glass fibres.

Many issues on natural fibre-reinforced polymer composites have been reported in the literature, particularly low melting point, high moisture absorption, poor adhesion and compatibility between fibre and matrix [104]. The key issue is matrix–filler compatibility, whic still needs to be addressed. Low OPF–matrix compatibility decreases the mechanical properties of final composites because polymers cannot interact with reinforcements containing polar moieties, such as OPF. The non-polar nature of OPFs results in the poor dispersion of the filler, insufficient adhesion and reduction in the fibre properties. Natural fibres, such as OPF, tend to agglomerate in the polymer matrix because of the hydrogen bonds of the hydroxyl groups, and the process results in poor fibre dispersion within the matrix and poor matrix–fibre interaction [108]. The non-polar hydrophobic nature of the polymer matrix exacerbates the dispersity of the polar fibre, which is hydrophilic by nature. For instance, Chaiwong et al. [54] found that the highest tensile strength in 5% NaOH-treated OPF–wheat gluten green composites, which showed good interfacial adhesion between OPF and the biopolymer matrix. This condition facilitated the transfer of stress from the matrix to the OPF. Poor polymer matrix–natural filler compatibility raises a major drawback for composites and limits its performance. The use of coupling agents or compatibilisers and surface modification technique is therefore essential because they facilitate chemical bonding across the

Table 4 – Comparison between the properties of natural and glass fibres [104–107].

Properties	Natural fibres	Glass fibres
Density	Low (0.45 to 1.60 g/cm^3)	Twice that of natural fibres (2.58 g/cm^3)
Cost	Low ($0.25 to $4.2/kg)	Higher than NF ($2.00 to $5.00/kg)
Renewability	Yes	No
Energy consumption	Low (48.33 MJ/kg)	High (3–5 MJ/kg)
Carbon dioxide neutral	Yes (0.4–0.7 kg/kg)	No (2.04 kg/kg)
Abrasion to machine	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Non-biodegradable
Thermal stability	Poor, need modification of fibre surface	High
Production	NF has lower environmental impact than GF	

*NF: natural fibre, GF: glass fibre.

matrix–filler interface and reduce the hydrophilicity of OPFs. The range of applications of the fibres can be increased by ensuring their uniform dispersion throughout the matrix.

5. Influence of fibre modification on the mechanical properties OPFs and their biocomposites

The utilisation of OPF improves the mechanical properties of polymer composites [40]. However, the main concern is the compatibility between the high hydrophilic nature of natural fillers and hydrophobic polymer in the composites. The interfacial adhesion between the filler and the matrix significantly influences the mechanical properties of composites, and a strong interaction is essential to provide good stress migration from the matrix to the fibres. Interfacial bonding has four types: (i) interdiffusion bonding (Fig. 5(a)), (ii) mechanical interlocking (Fig. 5(b)), (iii) electrostatic bonding (Fig. 5(c)) and (iv) chemical bonding (Fig. 5(d)). Thus, OPF modification can be implemented to enhance the adhesion between matrix and fibres and minimise the hydrophilicity of the fibres through physical, chemical and biological methods.

5.1. *Physical method*

Physical methods for treating fibres can efficiently change structural and surface features, improve thermal properties and influence composite mechanical bonding without changing their chemical composition [110,111]. These methods can be classified into three categories: mechanical treatment, solvent extraction treatment and electric discharge treatment [112]. The purposes of these treatments are to separate fibre bundles into individual filaments and improve fibre surfaces for composite applications [113]. For instance, surface oxidation activation is achieved by changing the surface energy of the cellulose fibres through using a combination of corona discharge and cold plasma treatment. Different gases can be used to induce surface cross-linking, increase or decrease surface energy and produce reactive free radicals and groups [114]. Table 5 highlights the benefits of physical treatments. These treatments offer many

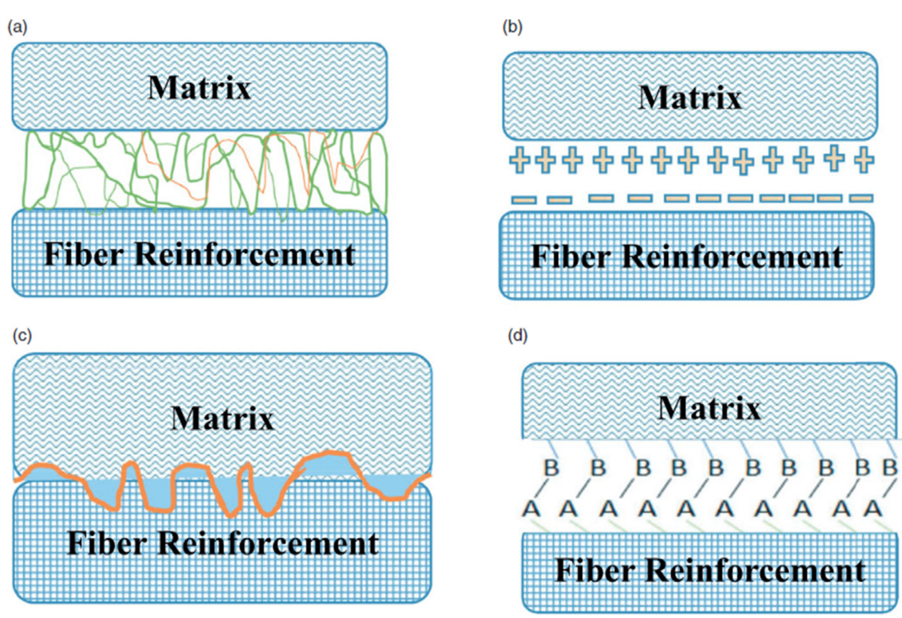

Fig. 5 – Types of interfacial bonding, (a) molecular inter diffusion, (b) electrostatic bonding, (c) mechanical interlocking and (d) chemical bonding [109].

Table 5 – Effect of some physical treatments on the mechanical properties of fibres [112].

Treatment	Advantage
Stretching	Heat treatment will improve the fibre strength and develop high tensile modulus
Plasma treatment	Fibres have stronger interaction with the matrix and enhanced the mechanical interlocking of the fibre-matrix in composites
Ultraviolet (UV)	Fibre-matrix interfacial along with mechanical properties of biocomposites are increased
Electron radiation	Improves the interfacial bonding of fibre and matrix due to free radicals, which ensure crosslinking between the fibre-matrix. Hence, composite materials possess good mechanical properties.
Corona treatment	Improved the compatibility between hydrophilic fibres and the hydrophobic matrix.

advantages. Specifically, they increase the mechanical characteristics and surface area of physically treated fibres.

5.2. *Chemical method*

Apart from physical methods, the interfacial bonding of fibres and polymers can be improved through chemical surface modification. The objective of the chemical treatment of fibres is to expose the sensitive and reactive functional groups present on the fibre surface and introduce the hydrophobic features of cellulosic fibre [115]. This process occurs when various chemicals react with the hydroxyl groups (–OH) in the fibres, resulting in an irreversible alteration in the molecular structures of the fibre components. Moreover, chemical treatment facilitates the removal of lignin, hemicellulose, wax and oils from the fibre surface, results in a strong interaction between fibres and matrices and provides composite materials with excellent mechanical performance [40,116]. Chemical surface modification approaches for natural fibres, including alkaline, acidity and coupling agent treatments, have been widely reported in the literature and used in overcoming this limitation. The studies listed in Table 6 revealed that the chemical treatment of OPFs improves compatibility, hydrophobicity and interfacial bonding and thus improves the mechanical properties of fibres.

5.3. *Physicochemical method*

Physicochemical treatment combines physical and chemical treatments to enhance chemical productivity and facilitate fibre bundle separation. These types of treatments can produce clean, fine natural fibres or fibrils with a high cellulose content and have mechanical properties similar to those of pure cellulose fibres and can substantially improve the visual and mechanical properties of OPFs. Physicochemical surface treatments result in excellent compatibility and interface bonding by eliciting a multitude of physical and chemical changes that improve surface free energy, mechanical interlocking at the composite interface and composite mechanical properties. These treatments are recommended for potentially significant changes in fibre surface properties with improved

Table 6 – Chemical treatments used in OPF modification.

Method	Conditions	Mechanical properties improvement	Ref.
Alkaline	1% and 5% NaOH for 2 h at room temperature	• The composite of wheat gluten and fibre treated with 5% NaOH showed the highest tensile strength (13.75 MPa).	[54]
Silane	2% triethoxy(ethyl) silane for 3 h	• Tensile strength of OPF was increasing around 120% after treatment by silane as compared with untreated fibre.	[117]
Peroxide	4% H_2O_2 for 3 h (ratio fibre to H_2O_2 = 1:20)	• The highest interfacial shear strength improvement in OPF treated with 4% H_2O_2 which 6.32 MPa.	[117]
Isocyanate	20% Poly[methylene(polyphenyl isocyanate)] (PMPPIC)	• Composites with extracted EFB fibres, with the incorporation of PMPPIC show the highest flexural strength enhancement of about 20% than unextracted fibre.	[118]
Maleated coupling agent	PP, OPMF (75 and 85%) and coupling agents (maleic anhydride-grafted poly (styrene-ethylene/buta diene styrene) (SEBS-MA) and maleic anhydride-grafted polypropylene (MAPP)) were blended in mixer at 5250 rpm for 1–2 min	• MAPP has a stronger influence on the flexural properties than SEBS-MA in both 75wt% and 85wt% composites. • The SEBS-MA improved the impact strength in both composites of 75 and 85wt% of OPMF, if compared with composites with MAPP	[119]
Benzoylation	OPF suspended in 10% NaOH solution and agitated vigorously with 50 ml benzoyl chloride for 15 min.	• Benzoylated OPF improved the tensile properties and impact strength of composites as compared to the untreated fibre.	[53]

Table 7 – Mechanical properties of OPF-reinforced thermoset polymer composites.

Fibre loading/types	Matrix	Treatments/Conditions	Flexural		Tensile		Impact	Ref.
			Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/m^2)	
Oil pam ash 30 wt. % (300 mesh)	Epoxy	• OPA loaded in epoxy resin	120.0	5.9	61.6	1	3.3	[126]
Oil palm empty fruit bunch + woven kenaf 35 wt. %	Epoxy	• OPF woven kenaf fabrics fabricated via hand lay-up techniques using epoxy resin as the polymer matrix. • The composition was hot-pressed for 15 min at 120 °C under the constant pressure of 250 bars.	115.8	8.7	55.7	2.9	1.78 J (Fractured energy)	[127]
Oil palm empty fruit bunch + Kevlar	Epoxy	• Kevlar/OPF epoxy fabricated via hand lay-up technique and pressed for 24 h. • The curing process took place in the oven for 3 h at 80 °C. • All hybrid composites were subjected to different doses of gamma irradiation (0, 25, 50, 150 kGy)	41.2–66.9	4.4–5.7	33.0	1.6	–	[128]
Empty fruit bunch 5 vol.% (10–20 mm)	Epoxy	• Epoxy/EFB composites were fabricated via hand lay-up technique and pressed until the thickness of 3 mm • The curing time is 24 h at room temperature	40.9	3.2	29.9	1.4	–	[28]
Oil palm ash 50% (0.28 mm)	Urea-Formaldehyde (UF)	• OPF and UF resins were mixed and hot-pressed at 175 °C for 1200 s followed by the cold press for 1200 s at 28 °C	1.4	–	3.9	1.2	–	[129]
Oil palm ash + oil palm trunk 2% (70–200 nm)	Phenol-Formaldehyde (PF)	• The resin embedded with OPA nano-particles used as adhesive glue for hybrid OPT/EFB plywood and fabricated via cold press	27.0	4.0	–	–	3.5–4.5	[130]
Empty fruit bunch 40 wt.% (40 mm)	Phenol-formaldehyde (PF)	• Different chemical modifications were subjected to EFB fibre include mercerization, acrylonitrile, acrylation, latex coating, permanganate treatment, acetylation, and peroxide treatment • The fibre was chopped and randomly spread in a mold cavity and impregnated with PF resin • The composite was hot-pressed at 100 °C.	16–75	0.7–3.9	13–40	0.5–1.2	–	[82]
Oil palm shell 30% (1.0–2.8 mm)	Unsaturated polyester (UPE)	• OPS reinforced UPE were mixed with the addition of 1 vol.% of methylethylketone peroxide (MKEP) and prepared via compression mold technique which was left to cure for 24 h.	–	–	20	8.5	–	[122]

Oil palm ash 30 vol. % (<300 μm)	Unsaturated polyester (UPE)	• OPA reinforced UPE were mixed with the addition of 1 vol.% of methyl-ethylketone peroxide (MKEP) and prepared via cold press technique which was left to cure for 24 h at room temperature.	—	—	12.2	7.5		[131]
Empty fruit bunch + kenaf 12 wt. % (2 cm)	Unsaturated polyester (UPE)/epoxidized oil palm (EPO)	• UPE/EPO blended prepared by mixing 85 wt.% UPE and 15 wt% of EPO. The mixture was stirred on the hot plate at a temperature of 55 °C. Benzoyl peroxide (hardener) was added to the mixture at 1.5 phr. • Kenaf and EFB fibre were treated with 6% NaOH solution for 3 h at room temperature. • Hybridized kenaf/EFB fibre mats were placed in an aluminum mold. UPE/EPO were poured until the resin-covered and wet all the area of the fibres. The composite were left cured in an oven at 100 °C for 2 h.	—	—	1.3	1.5	1.8	[132]

matrices and overcoming the hydrophilic nature of fibre surface properties [112].

5.4. *Thermal method*

Thermal modification is an environmentally beneficial alternative to chemical treatment because it is a chemical-free approach that produces zero toxic waste. Thermally modified fibres function on the basis the cell wall components undergo chemical alterations at high temperatures (over 150 °C). At these temperatures, a variety of reactions occur, including polysaccharide hydrolysis, oxidation, radical reactions and condensation processes. In thermal modification, different chemical reactions occur, and hemicelluloses are the first cell wall components altered by the temperature range typically used during the treatments [120]. The other two main components of the fibres, cellulose and lignin, are less affected. The key differences in treatments, apart from temperature, are in the process management or the modification medium used to include water vapor, nitrogen and vacuum atmospheres, as well as oil. However, lignin softening and the generation of lignin derivatives can enhance the degree of cross-linking in the cell wall, reducing the elastic properties of treated fibres and decreasing hygroscopicity. Moreover, thermally modified fibres become brittle compared with untreated fibres, showing lower bending and tensile strength but higher longitudinal strength and increased compressive strength and stiffness. The specific method of treatment can have a substantial impact on the properties of thermally treated fibres [121].

6. Mechanical performance of oil palm biocomposites

6.1. *OPF-reinforced thermoset polymer composites*

Thermosetting materials, such as epoxies, polyester and phenolic compounds, have been widely used in the fabrication of composites and development of various types of high-end products. In general, the application of thermoset is preferred because of its advantages, such as good mechanical and thermal properties, and the products are easier and cheaper to manufacture than thermoplastics [122,123]. To date, the demand for natural fibre-based composites has increased [124]. The incorporation of natural fibres particularly derived from oil palm biomass has attracted the attention of researchers and manufacturers because of their versatility in terms of types of the fibres and their ability to impart excellent properties to composite systems. Furthermore, the utilisation of waste biomass from oil palm with thermoset polymers turns waste materials into value-added products. Few factors can affect the mechanical performance of composite systems: tensile strength of the fibres, interfacial adhesion between fibres and matrices, the aspect ratio of fibre, orientation of the fibre and their dispersion into the matrix [125]. Table 7 shows the summary of the mechanical properties of OPF-reinforced thermoset composites.

Epoxy resins are the most important thermoset polymeric materials used in the manufacturing of composites, constitute

70% of the commercial thermoset market and are widely used as coatings, adhesives, electronic materials and structural materials [133,134]. Many researchers used epoxy polymers as matrices and incorporated them into various types of OPFs aiming to improve performance, especially in terms of mechanical properties. For example, Rizal et al. [126] utilised an agro-industry waste of oil palm ash as a microfiller and incorporated it into epoxy resins at different concentrations (0–50 wt.%) and sizes. Oil palm ash is a product of all oil palm waste biomass and is used as boiler fuel in pal mills for steam electricity generation. After incineration, approximately 5 wt.% of ash is collected, which is known as oil palm ash (OPA). In this study, different sizes of OPA microfillers were used, including 100, 200 and 300 mesh sizes with an average diameters of 138.64, 72.15 and 50.12 μm, respectively. The mechanical performance of the composites was observed through tensile, flexural and impact analysis. The results showed that 30 wt.% of filler loading of 300 mesh sizes showed optimum composition. However, the mechanical properties of the composites, decreased after high amounts of microfillers were added. This result indicated the effect of agglomeration that caused premature failure. By contrast, composites with small amounts of microfillers showed enhanced mechanical performance because of their high surface areas (4.6198 m^2/g), which are conducive to load transfer.

Some researchers investigated other approaches for enhancing the mechanical performance of composites. One of the techniques includes the ybridization of high-modulus and low-modulus fibres. This approach retains the excellent properties in terms of reinforcement and results [135]. The hybridisation can be performed using natural and synthetic fibres or using two types of natural fibres. Amir et al. [128] studied the effects of hybridising natural fibres and synthetic fibres and using OPF, Kevlar and epoxy as the polymer matrix resin. The study focused on evaluating the effect of the layering sequence and gamma radiation on the mechanical performance and morphology properties of the hybrid composites. The hybrid composites were fabricated with the hand lay-up method, and different layering sequences were used. Exposure to different gamma radiation doses (25, 50 and 150 kGy) was performed. Two types of sequences were used in this study. First, OPFs were used as the core and were sandwiched between two Kevlar fabrics (K/OP/K). In the second type, Kevlar was used as the core material and sandwiched between the layers of OPF (OP/K/OP). The different layering patterns of the fabricated hybrid composites are depicted in Fig. 6. Overall, the layering sequences increased mechanical performance when OPF was used as the core materials compared with those when Kevlar was used the core material. The tensile and flexural properties of the hybrid composites showed improvement after irradiation with low gamma radiation. Figure 7 displays that morphology of the improved fibre/matrix adhesion after radiation treatment and the improved tensile and flexural properties of oil palm/Kevlar/epoxy composites. The hybrid composites with the K/OP/K pattern possessed better tensile strength, which was 48.1% higher than that in the OP/K/OP pattern. This result attributed to the effect of Kevlar, which acted as the skin of the laminate and was in the woven form compared with OPF, which presented a fibre mat showing random orientations. The high tensile strength of Kevlar (3600 MPa) as compared with OPF (248 MPa) contributed to the high tensile strength and increased capability to withstand high tensile stress as compared with that observed in OP/K/OP layering. The tensile strength of the hybrid composites increased by 20.2% after irradiation at 25 kGy. Meanwhile, the K/OP/K pattern showed good flexural properties, especially are irradiation at up to 50 kGy because of cross-linking, which enhanced interfacial adhesion.

The effect of hybrid composites was performed by Hanan et al. [127], who used the OPF/woven kenaf-reinforced in an epoxy matrix. The bilayer hybrid composites were prepared at different weight ratios of OPF/woven kenaf fabrics reinforcements of 50/0 (T1), 35/15 (T2), 25/25 (T3), 15/35 (T4) and 0/50 (T5) with the hand lay-up technique followed by hot pressing with mould dimension of 300 mm × 300 mm × 5 mm. The mechanical properties of the hybrid composites were analysed through series of tests, including a tensile test. The tensile of individual fibre was included for the comparison. Kenaf fibres (T5) possessed higher tensile strength than OPF (T1) mainly because of it has a stronger longitudinal orientation and the stiff kenaf fibre improved load-carrying capacity and mechanical strength. The tensile test of the hybrid composition showed composition T4 (15 OPF/35 woven kenaf fabrics) and had the optimum strength relative to other hybrid composites close to the T5. The flexural strength of T4 was higher than that of T5. The values were 115.8 and 111.68 MPa, respectively. T1 showed the highest impact strength, whereas T4 showed the lowest. These findings were mainly attributed to the fibre orientation and chemical composition of the oil palm EFB. Moreover, another phenomenon contributed to these results. The randomly oriented EFB had moderate interfacial interaction with epoxy. This interaction is an important factor for improving impact strength. Through mechanical analysis, the hybrid composites were found to have potential used in non-load-bearing applications.

Apart from epoxy, adhesive glues, such as phenol-formaldehyde (PF) and urea-formaldehyde (UF), are widely used in the fabrication of plywood, fibreboard and sandwich composite panels. For example, Richard et al. [129] utilised UF resin incorporated with an oil palm frond with the objectives of providing value to agricultural waste products with mechanical performance comparable to those of synthetic composites. The OPF fibre-reinforced UF resin was prepared by

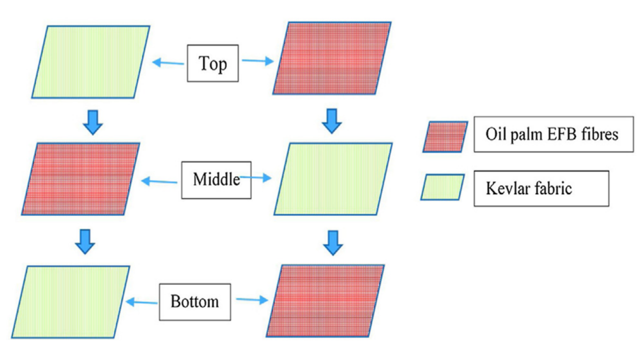

Fig. 6 – Different layering patterns of the fabricated OPF/Kevlar/epoxy hybrid composites irradiated with different radiation doses [128].

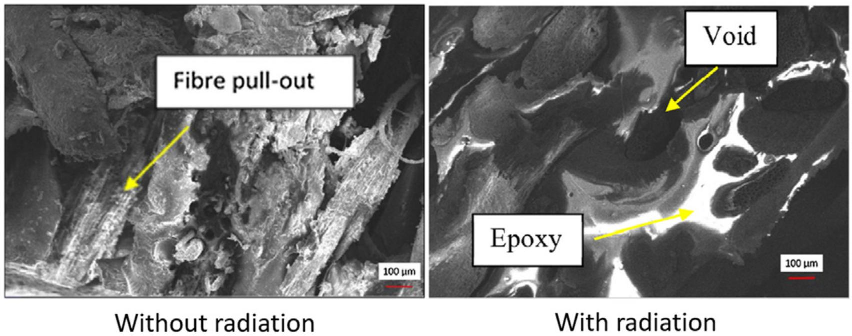

Fig. 7 – Effect of radiation intensity on the OP/Kevlar-reinforced epoxy composites [128].

mixing the materials and hot-pressing according in a mould size of 200 mm × 200 mm × 6 mm. Two different fibre loads (40% and 50%) and 0.28 mm mesh size with a targeted fibreboard density of 0.7 g/cm^3 were used. Mechanical analysis was performed. The results showed that 50% OPF loading provided the highest tensile and flexural strength of 3.874 and 1.4306 MPa, respectively. However, they expected the mechanical performance to drop after a high fibre load was used in the composite system. The reason for this drop was fibre pullout, as shown in Fig. 8. It occurred because insufficient wetting between the fibres and matrix decreased the strength of the composite.

Micro- and nanosize fillers are incorporated into adhesives to enhance the strength of adhesive matrices, reduce the formation of voids and improve water–resistant properties [136]. This method was later adopted by Nuryawan et al. [130] in their study by enhancing the properties of PF resin using nanoscale OPA. The PF resins filled with OPA nanoparticles were prepared and used as glues for the layers of OPT and EFB hybrid plywood. The hybrid plywood was fabricated with the hand lay-up method and by layering 5-ply hybrid plywood with dimensions of 320 mm × 320 mm × 10 mm. The schematic arrangement of the 5-ply OPT veneer and EFB mat used to produce hybrid plywood are depicted in Fig. 9. The layers were glued using PF enhanced with OPA nanoparticles, and glue was spread on a 400 g/m^2 area. The layers were cold-pressed for 10 min. The moisture content of the hybrid composites showed lower moisture content and water absorption capacity, especially at 5% of OPA nanoparticles loading, than plywood-veneer commercial plywood. The resin that permeated into the gap and porous spaces between the veneers and fibre mat facilitated interlocking between veneer layers. The presence of OPA nanoparticles further filled the spaces and impeded moisture absorption. The addition of OPA nanofiller improved mechanical performance, especially at 2% of OPA loading, resulting in the optimum strength of the hybrid composites. However, further increasing the amount of OPA nanoparticles to more than 2% reduced the mechanical performance of the hybrid composite because of agglomeration.

Another important thermosetting resin used for composite development is polyester. Unsaturated polyester (UPE) has been widely used because of its advantages over other thermoset resins in terms of mechanical, thermal and room temperature cure capability; low cost; and transparency [137]. Sahari and Maleque [122] utilised UPE resin as a matrix to reinforce OPS at different volume fractions (10%, 20% and 30%). The highest tensile modulus of UPE/OPS composites was obtained at 30 vol.% of OPS, with a value of 8.50 GPa. The tensile strength of the composites showed significant improvement as the volume fraction of OPS increased in the composites system. A similar study was performed by Sahari and Maleque [131], who used different types of oil palm biomass, such as OPA, at different volume fractions (0, 10, 20 and 30 vol.%). The addition of OPA presented a trend opposite to that obtained in a previous study that used OPS, which showed a decrement trend as the amount of filler increased. The author attributed reduction in strength to the physical properties of OPA, which has large particles and disrupts interaction between matrices and fillers.

In a separate study, a blend polymer of unsaturated polyester (UPE) and epoxidised palm oil (EPO) were used to reinforce hybrid kenaf and EFB fibre [132]. The effects of fibre fraction on the mechanical and thermal properties of the hybrid composites were studied. Both types of reinforcement were treated with an alkaline solution before being incorporated in the blended polymer matrix and pressed with a hydraulic hot-pressed machine. Three components of kenaf/EFB hybrid composites were determined (100/0, 90/10, 70/30 and 50/50 [wt.%]) at different fibre weight fractions (9, 12 and 15 wt.%) reinforced in the UPE/EPO resin. The mechanical

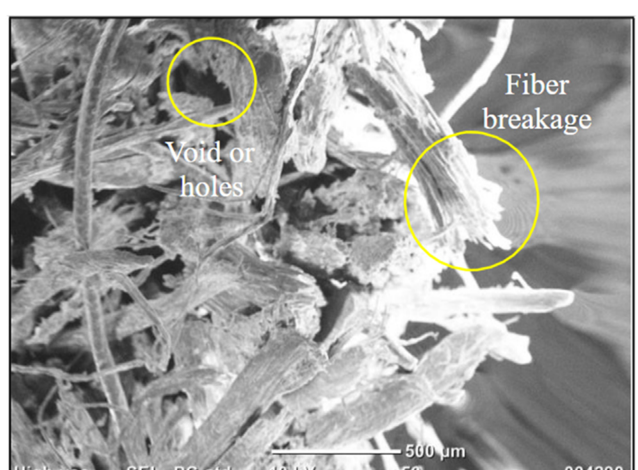

Fig. 8 – Morphological analysis of 50wt% of OPF reinforced UF composites [129].

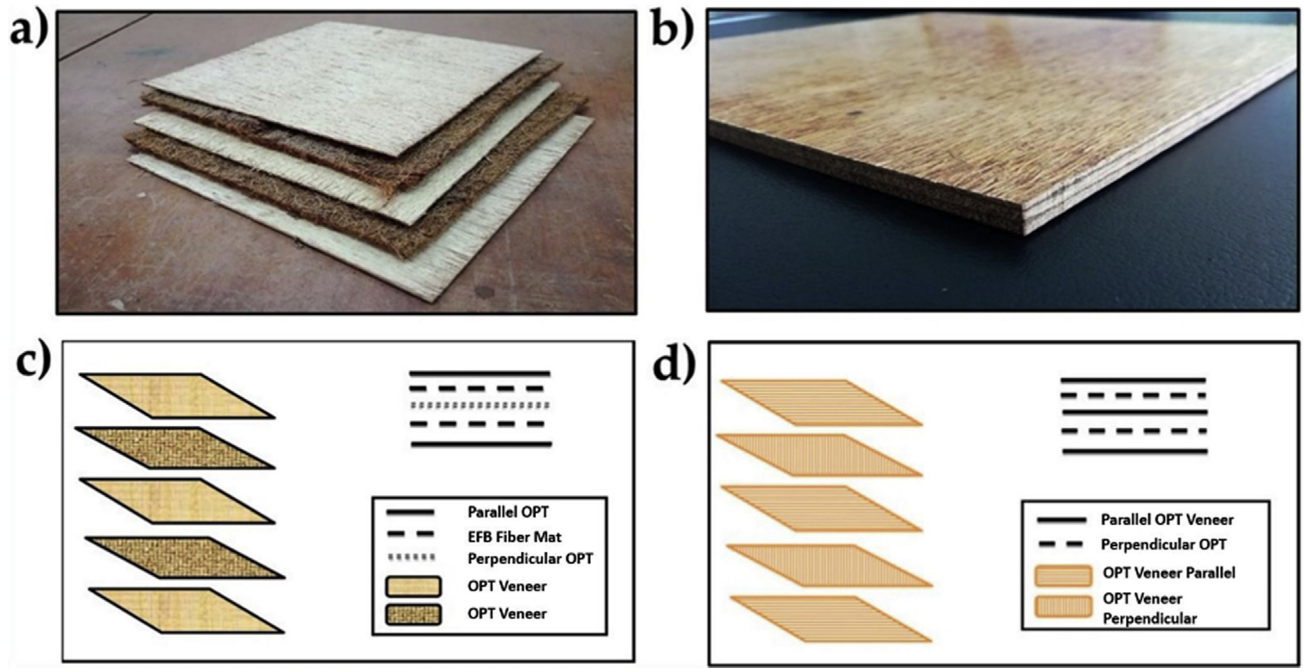

Fig. 9 – OPT/EFB hybrid plywood with the addition of oil palm ash (OPA) nanoparticles, with phenol-formaldehyde (PF) resin as a binder, in the form of (a) layering pattern of five plywood hybrid before pressed and (b) hybrid plywood composites. The schematic arrangement (c) hybrid plywood and (d) schematic arrangement of OPT veneer plywood [130].

study revealed that the high composition of EFB in the kenaf/EFB hybrid fibre increased the tensile properties, elongation at break and impact strength of the composites, particularly after the addition of fibres at 9 and 12 wt. %. A high fibre fraction (15 wt.%) and hybridisation (50/50) resulted in the lowest mechanical properties (stiffness, toughness and impact strength). The 12 wt.% fibre fraction at 70/30 (kenaf/EFB) was the most suitable for structural applications.

6.2. *OPF-reinforced thermoplastic polymer composites*

To date, the functions of lignocellulosic and cellulosic materials reinforced with thermoplastic composites have attracted considerable interest. Natural or lignocellulosic fibres are considered new-generation reinforcing materials as they are derived from renewable natural sources [138,139]. Oil palm biomass is an industrial product that can be obtained at a minimal cost. Its availability as an agricultural by-product has attracted the attention of researchers and manufacturers, who have attempted to fully utilise the biomass, thus providing a new era for research and development. Table 8 shows the mechanical properties of OPF-reinforced thermoplastic composites. Natural fibres, such as OPFs, exhibit low thermal stability, and their thermal stability depend on their chemical components, such as cellulose, hemicellulose and lignin during the melt process [140]. Approximately 60% of the thermal decomposition of most natural fibres occurs at 230–350 °C because of the break down of cellulose, hemicellulose and lignin. To solve the low degradation temperature of natural fibres, a chemical modification method is used to enhance thermal properties given that treatment facilitates interfacial bonding between fibres and matrices [141]. Improved fibre–matrix compatibility enables treated fibres to protect themselves from direct contact with temperature. In another case, the treated natural fibre-reinforced polymer composites mostly displayed low residual amounts because the partial washing out of lignin during the treatment process [142].

The application of OPF improves the mechanical properties of blended polymers. Ayu et al. [144] studied the effects of EFB fibre addition on poly(butylene) succinate (PBS)/starch/glycerol composite sheets. The hybrid composites were compounded using an industrial extruder, the temperature was set at 115–145 °C, and the rotation speed was 80 RPM. The melted compound then passed through a calendaring machine before sheet production. The fibre content played a major role in determining the mechanical properties of the composite sheet. The addition of 8 wt.% of EFB reduced the tensile strength because of incompatibility and dispersion problems. However, the tensile value gradually increased as the fibre content increased from 8 wt.% to 20 wt.% with the value of 15.96 MPa–20.18 MPa, respectively, because of the addition of glycerol and localisation of a compatibiliser at the interface would impart better morphology surface. A similar trend was found in the flexural strength of the composite sheet, which showed improved stress absorption. A morphological analysis was conducted on the OPF green composites, as shown in Fig. 10. Fig. 10 (a) shows the smooth and regular image of raw PBS, and Fig. 10 (c) and (d) show that starch particles and fibres are not well dispersed on the PBS matrix, causing weak bonding and indicating that fracture occurs easily.

Ramli et al. [138] investigated the effect of fibre type, fibre loading and the effect of coupling agents upon the

Table 8 – Mechanical properties of OPF-reinforced thermoplastic composites.

Fibre loading/size	Matrix	Treatments/Conditions	Flexural		Tensile		Impact	Ref.
			Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/m^2)	
OPF (frond, EFB, trunk) 40 wt.%	PP	• OPB/PP composites with the addition of MAPP coupling agents compounded twin-screw extruder at 170–190 °C. The composite is compounded through injection molding.	~30	0.3–0.4	25–30	35–40	0.57–0.60	[138]
OPF + rice husk 10 wt.% (200 mesh)	PP	• RH and OPF undergo two types of treatment; mercerization and acetylation • RH/OPF reinforced PP were mixed in a mixing container at temperature 165–175 °C. The mixture was then poured into a mold with and pressure of 32 MPa.	–	–	22–34	0.25–0.30	0.54–0.82	[143]
Oil palm mesocarp 5-25 wt.% (300 mesh)	LLDPE	• OPMF/LLDPE were fabricated through the hand lay-up method. The mixture then was heated in the aluminum mold with the dimension of 295 x 210 × 6 mm at 150 °C for 20 min.	–	–	7.3–9.0	0.2–0.3	97–160	[57]
Empty fruit bunch 8-25 wt.% (300–600 μm)	PBS/starch/glycerol	• The hybrid composites were compounded using an industrial extruder and the temperature was set to be between 115 and 145 °C with the rotation speed of 80 RPM. • The melted compound then passes through a calendaring machine before producing a sheet.	27.2–32.6	0.9–1.1	16–20.2	0.3–0.5	–	[144]
OPF	ABS	• OPF fibre was alkaline treated before mixing with ABS polymer matrix • The extrusion of composites was done using a single screw extruder to produce OPF/ABS filament • The specimen design was created and imparted through the software before the printing process • The OPF/ABS composites were printed using an FDM 3D printer to print tensile and flexural specimen	19.4	6.4	20.6	1.1	–	[58]

(continued on next page)

Table 8 – (continued)

Fibre loading/size	Matrix	Treatments/Conditions	Flexural		Tensile		Impact	Ref.
			Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/m^2)	
Oil palm frond fibre 30 wt.% (2–3 mm) Oil palm frond powder 30 wt.% (60–90 μm)	TPU	• OPF fibre was alkaline treated with 2% NaOH and soaked for 30 min. The fibre then dried at 100 °C for 6 h • Short OPF was cut to 2–3 mm whilst the OPF powder was crushed and sieved with a 60-micron mesh filter • TPU reinforced OPF fibre/powder were melted compounded using an internal mixer at 190 °C at 60 rpm. The mixture was then hot pressed at 190 °C for 7 min at a pressure of 95 kg/cm^3.	5.5 5.2	– –	9.2 8.3	– –	6.0 J/m^3 (absorbed energy) 5.5 J/m^3 (absorbed energy)	[145]
Oil palm empty fruit bunch 10–40 wt.% (75 μm)	Un-plasticized PVC	• PVC and EFB were compounded via a high-speed mixer for 10 min. • The dry-blended PVC compound was sheeted using a two-roll mill at 165 °C for 10 min. • The mill sheet was hot-pressed at temperature and pressure of 180 °C at 120 kg/m^2, respectively for 5 min.	55–69	2.8–3.3	–	–	7–11	[146]
Empty fruit bunch + glass fibre 25 wt.%	PP	• PP reinforced with EFB and glass fibre were fabricated with the proportion of EFB and GF to be 75% and 25%, respectively • Three coupling were used; Epolene (E–43), poly(methylene-polyphenyl isocyanate) (PMPPIC), and 3-(trimethoxysilyl) propylmethacrylate (TPM) • The materials were compounded in an internal mixer at 175 °C for 20 min at a rotor speed of 20 rpm. • The compound then pre-heat and pressed into the mold with the dimension of 160 x 160 × 3 mm at 175 °C for 10 min.	30–33	2.7–3.3	15–18	7.9–8.1	–	[118]

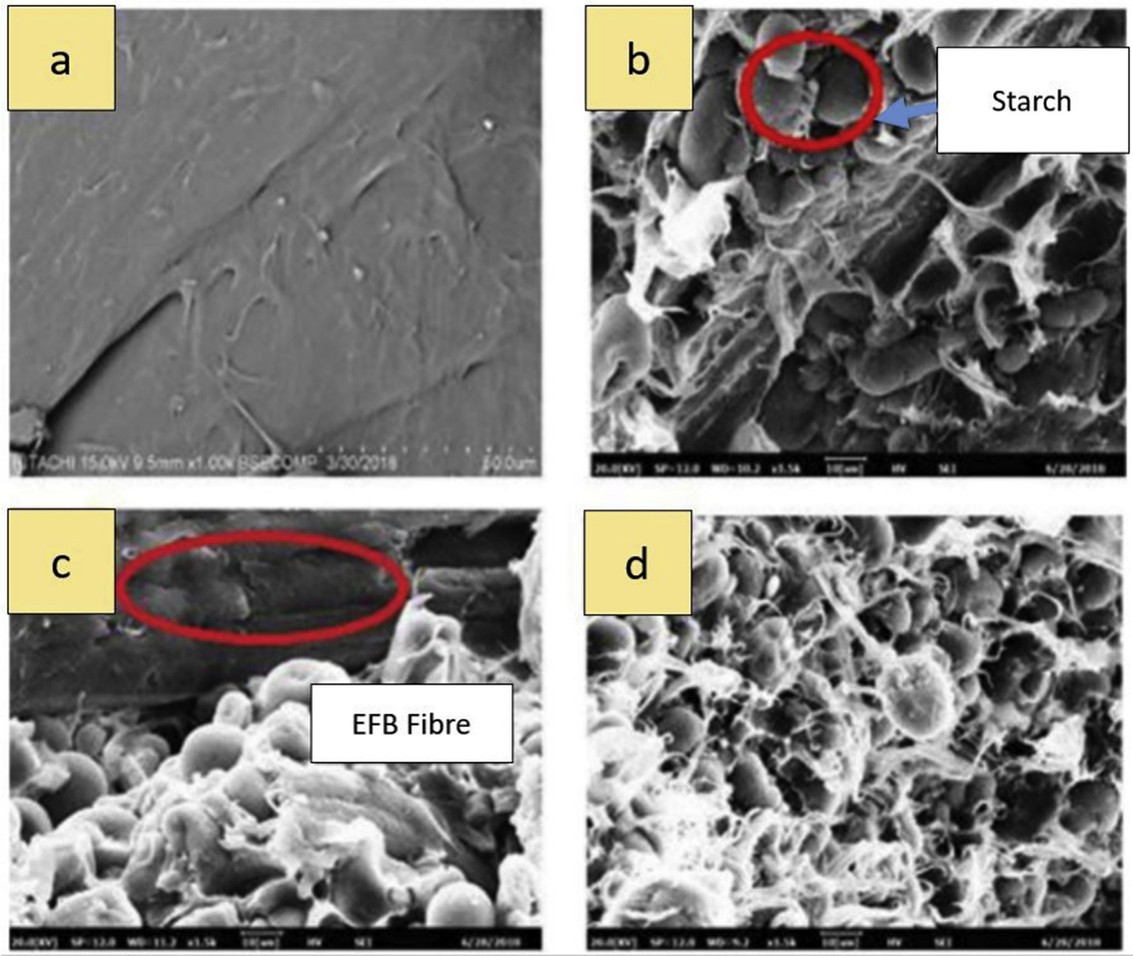

Fig. 10 – SEM analysis (a) Raw PBS (b) P/EFB (70/30) (c) P/EFB (60/40) (d) P/EFB (50/50) [144].

performance of OPB reinforced in polypropylene (PP) composites. A coupling agent, maleic anhydride grafted polypropylene (MAPP), was used to enhance the interfacial properties of the fibres and polymer matrix. It enhanced the mechanical properties of the composites. OPBs include empty fruit, frond and trunk and were compounded into PP with a twin-screw compounder at 170–190 °C. Various OPB fibre amounts (10, 20, 30 and 40 wt.%) were extruded and pelletised. Significant differences were observed in tensile and flexural properties, and trunk/PP composites showed the highest value. This finding was attributed to the chemical and physical characteristics of different types of fibres from a different portion of OPB. The addition of a coupling agent increased the tensile and flexural performance of the composites. However, the maximum improvement of tensile and flexural strength was found after the addition of 3 wt.% MAPP with 30% fibre content. The improvement of mechanical properties after the addition of MAPP was attributed to enhanced interfacial bonding between the fibre and the matrix. In a separate study, the effect of chemical modification on PP hybrid composites reinforced with rice husk (RH) and stripped OPF (OPEFB) was studed by Hassan et al. [143], who used two different chemical treatments (mercerisation and acetylation). The composition of the hybrid composites comprised 10RH/10OPEFB, 20RH/10OPEFB, 10RH/20OPEFB and 20RH/20OPEFB, which compounded at a temperature range of 165–175 °C and subsequently moulded at a pressure of 32 MPa. The tensile properties of the hybrid composites showed higher values for the acetylated fibre composites compared to that mercerised fibre composites. Meanwhile, the crude fibre composites that consist of untreated fibre presented the lowest tensile properties. The improved properties of the acetylated fibre composites were attributed to the enhanced interfacial adhesion between the fibre and matrix. Meanwhile, the mercerisation fibre composites presented better tensile performance than the crude fibre composites because of the removal of impurities, waxes and part of lignin. The removal of these components improved fibre–matrix interaction. A similar finding was obtained for the impact properties of hybrid composites. Treated hybrid composites improved impact strength and stress absorption during the impact and impeded crack propagation reducing the number of voids.

Other than common oil palm biomass utilised for the production of composites, oil palm mesocarp have been used as a reinforcement material to enhance the mechanical properties of thermoplastics. Oil palm mesocarp is usually obtained from a processing mill as waste or used locally for cooking. Olusunmade et al. [57] and co-workers attempted to utilise OPMF waste and incorporate it into linear low-density polyethylene (LLDPE) to study the effect on mechanical

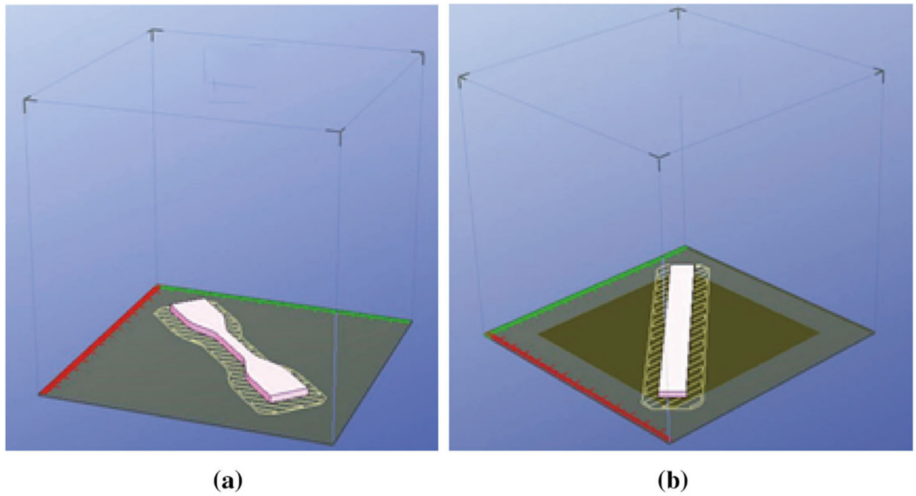

Fig. 11 – (a) Tensile and (b) flexural specimen design that used to be printed via FDM 3D printer [58].

properties. The OPMFs were initially washed and dried before they were used in composite fabrication. The fibres were pulverised and filtered to a sieve with a pore size 300 μm. Fibre content in the composites was 5–25 wt.%. The composites of OPMF/LLDPE were fabricated with the hand lay-up method. The mixture was heated in an aluminium mould with dimensions of 295 mm × 210 mm × 6 mm at 150 °C for 20 min. The mechanical properties of the composites were presented through tensile and impact performance. Overall, the addition of OPMF decreased the tensile and impact strength of the composites by 36.78% and 39.07%, respectively, as the fibre loading reached 25 wt.%. An increased value of tensile modulus was reported as the fibre content increased. This result indicated an increase in the stiffness of the composites after the addition of OPMF fibres. The extremely high stiffness properties of the composites led to brittle properties, which impeded the deformability of the interface between fibre and matrix. Therefore, the addition of a coupling agent or chemical treatment will enhance the incompatible properties of the two phases and improve the dispersibility of fibres in polymer matrices.

To date, the production of composites is showing tremendous leap of revolution. Through conventional types of fabrication, composite materials can be produced through additive manufacturing technology (known as 3D printing). This technique has become one of the favourable methods for manufacturing components of complex geometries. Ahmad et al. [58] adopted the 3D printing technology to fabricate OPF incorporated in the thermoplastic acrylonitrile butadiene styrene (ABS) as a composite filament for fused deposition modelling (FDM) method. The OPF fibre was treated with NaOH solution for 2 h before mixing with ABS polymer. FLD25 filament extrusion machine was used to extrude wire from OPF/ABS composites. This extrusion machine consisted of a single screw extruder with a 1.75 mm die. During the extrusion, the 1.75 mm OPF/ABS composite filaments were produced, which were used to print tensile (Fig. 11(a)) and flexural (Fig. 11(b) specimens. The composites were then printed using an FDM 3D printer (UP plus 2 model). The tensile properties of the composites were improved by 4% relative to those of a virgin ABS. In addition, the elongation performance of the composites improved relative to that of the virgin ABS. However, the flexural properties of the OPF/ABS composites decreased by 45%. The possible reason was the stiffness imparted by the addition of OPF fibres in the composite system.

6.3. OPF-reinforced biopolymer composite

The effect of petroleum-based polymers on the environment has drawn the attention of researchers and manufacturers into finding alternatives to polyolefins. The use of bio-based and biodegradable polymers for composite production is an option. Biodegradable plastics can be defined as plastics that can be degraded biologically by microorganisms, such as bacteria and fungi [147]. This term can be applied if a polymer is readily degraded to carbon dioxide and water. In developing sustainable packaging plastics, especially for short-term use, bio-based and biodegradable plastics are favourable. Biodegradable polymers can be produced from renewable resources with various techniques and methods [148]. However, these plastics need to be improved before being used in several applications given that some characteristics of these bioplastics do not match with commercial polymers characteristics [149,150]. Most of biopolymers have a thermal instability characteristic. At a high temperature (~150 °C), the glucose links of the starch-based polymer start to break apart. A t a low temperature, retrogradation occurs. This phenomenon makes the resulting starch-based films brittle. PHAs are known to have a narrow processing window because their melting and degradation temperatures are nearly equal [149–151]. Thus, the processability of this polymer for commercialisation remains difficult, and inherent brittleness of biopolymers largely impedes its wide applications. The brittleness and low mechanical strength of biopolymers make them difficult to replace polyolefins as packaging materials [152]. To overcome this problem, bi-layer or the use of multicomponent films with good mechanical properties have been developed, which make biopolymers suitable for several applications. Blending with lignocellulosic fibres, including OPF,

Table 9 – Mechanical properties of OPF-reinforced biopolymer composites.

Fibre loading/type	Matrix	Treatments/Conditions	Flexural		Tensile		Impact	Ref.
			Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/m^2)	
1 wt% of EFB fibre	PLA	Addition of inorganic nanosilica	–	–	34.0	1.375	–	[154]
1 wt% of EFB fibre	PLA	Addition of organic nanosilica	–	–	39.0	1.475	–	[154]
50 wt% of frond fibre	TPS	Ionic liquid	8.5	0.925	–	–	–	[155]
20 wt% of mesocarp fibre	TPS	Untreated	–	–	0.8	0.25	–	[156]
10 wt% of mesocarp fibre	TPS	Alkali treated	–	–	0.9	0.10	–	[156]
20% of mesocarp fibre	PHA	Untreated	–	–	13.0	3.35	–	[157]
20% of mesocarp fibre	PHA	Coupling with maleic anhydride	–	–	24.0	4.25	–	[157]

has received considerable interest [153]. Moreover, fibre treatment, fibre loading and manufacturing process can influence the mechanical properties of biopolymer composites. Most studies have shown that the mechanical properties of biopolymer composites were enhanced relative to those of neat polymers. Table 9 summarises the mechanical properties of OPF-reinforced biopolymer composites.

Salim et al. [158] discovered the effect of OPEFB addition on the mechanical properties of PHA composites. In their study, poly(3-hydroxybutyrate-co-3-hydroxyvalerate) was used as a PHA. The composites with 35 wt.% OPEFB fibre contents had the highest tensile strength compared with 30 and 40 wt.% of OPEFB in the PHA composites. Baskaran et al. [159] had investigated the influence of steam treatment on the properties of particleboard made from oil palm trunk containing PHA. They had found that the addition of PHA to the particle board enhanced the modulus of rupture, internal bond strength and dimensional stability of the panels. The highest modulus of rupture and internal bond strength values of 8.76 and 1.02 MPa were determined for the panels containing 10% PHA, respectively.

The effect of addition of coupling agent in OPF-reinforced PHA composite was investigated by Wu et al. [157]. In their study, maleic anhydride was used as a coupling agent in their study. Initially, the maleic anhydride was grafted with PHA before it was blended with OPF. Interestingly, composites with maleic anhydride-grafted PHA exhibited noticeably excellent tensile strength and interfacial adhesion compared with those of untreated PHA because of the compatibility of maleic anhydride-grafted PHA with OPF. The dispersion of fibre in the maleic anhydride-grafted PHA matrix was highly homogeneous as a result of condensation reactions.

Siyamak et al. [160] developed a OPEFB fibre-reinforced PBAT with various fibre loadings of 10–50 wt.%. The results showed that 40 wt.% of OPEFB fibre loading improved the tensile properties of the composite. The effects of chemical treatments and various organic initiators on the mechanical of composite containing 40 wt.% OPEFB fibre were examined. The succinic anhydride-grafted OPEFB fibre at a low weight percentage gain in the presence of 1 wt.% of dicumyl peroxide initiator significantly enhanced the tensile and flexural properties of the composite (up to 24%) compared with the untreated OPEFB fibre-reinforced composites. Recently, Yang et al. [161] researched the effect on the mechanical properties of TPS composite blended with treated OPEFB fibre and citric acid. Treated OPEFB fibre was obtained through thermal and alkali treatments. The addition of citric acid promoted the compatibility between OPEFB fibre and TPS effectively. The incorporation of treated OPEFB fibre and citric acid considerably improved the tensile strength of the composites. The tensile strength increased significantly from 0.45 MPa to 1.99 MPa after the conent of the treated OPEFB fibre was increased from 0 wt.% to 20 wt.%. The treated OPEFB fibre exposed hydroxyl groups on the surface and enhanced the interactions of TPS through hydrogen bonds. Additionally, the uniform dispersion of treated OPEFB fibre in the blends, which was verified by morphological analysis, improved reinforcement.

The PLA-based composites containing OPF have garnered the attention of researchers. The development of OPF-reinforced PLA composite was discovered by Haafiz et al. [162]. In their work, PLA was blended with cellulose isolated from OPF with the solution casting method. The synthesised composites were characterised in terms of tensile properties. The incorporation of cellulose into the PLA matrix resulted in the decrement in the tensile strength and elongation at break of the composites as compared with pure PLA. However, the Young's modulus increased by approximately 30%. The decrement in the tensile strength was due to the poor interfacial adhesion between the cellulose and the matrix.

Yee et al. [154] prepared a OPEFB fibre-reinforced PLA composite by adding nanosilica and using the solvent casting method. Nanosilica was as the filler because of its contribution to thermal stability and mechanical properties. The tensile strength of the neat PLA decreased from 48 MPa to 29 MPa after 1.5 wt.% OPEFB fibre was introduced to the PLA matrix. The tensile strength of the composite decreased with increasing of OPEFB fibre load. This trend can be explained by the hydrophilic nature of lignin in the OPEFB fibre. Thus OPEFB fibre is incompatible with PLA matrices. However, nanosilica increased the tensile strength as fibre load content increased.

Campos et al. [156] studied the effect of raw and chemically treated OPMF on thermoplastic cassava starch properties. TPS composites using raw OPMF showed an improvement of 193% in the elastic modulus and 153% for maximum stress, whereas the elongation at break was constant relative to the neat TPS matrix. The high improvement in the mechanical and thermal properties of the TPS matrix by the raw OPMF was due to the presence of silica, which influenced the interaction of the matrix and OPMF. The present work showed that TPS composites with 10 wt.% OPMF had greater mechanical properties than alkaline treated OPMF. The mechanical tests result of TPS composites using raw and alkali-treated OPMF indicated that the raw ones can be incorporated in the TPS matrix without previous treatment. Mahmood et al. [155] investigated the effect of ionic liquid (IL) treatment of OPF fibres on the mechanical performance of TPS composites. ILs are promising green solvent for OPF disintegration. In their work, OPF fibre was treated with IL [emim][dep] (1-ethyl-3-methylimidazolium diethyl phosphate) and IL [bmim][Cl] (1-butyl-3-methylimidazolium chloride). The treated OPF fibre composites exhibited excellent strength and modulus relative to the untreated OPF fibres, as indicated by the flexural test. The flexural strength of the composite board fabricated from the untreated OPF fibre was 5 MPa. After IL treatment, the flexural strength increased to 8.5 and 6.8 MPa for IL treatment with [bmim][Cl] and [emim][dep], respectively. In addition, the flexural modulus was improved from 530 MPa for composite made from untreated OPF fibre to 925 MPa for [bmim][Cl]-treated OPF fibre composite and 790 MPa for [emim][dep] treatment.

6.4. *Hybrid OPFs reinforced polymer composites*

Hybrids of OPFs and other lignocellulosic and synthetic fibres have been extensively studied. Many scientists, engineers and researchers are working together to develop high-performance natural fibre polymer composites that can be used in various applications, such as medical devices, structural construction and automotive components. Fibre hybridisation is a favourable and synergic approach to strengthen and toughen the composite materials. By hybridising two or more fibre types, these hybrid fibre-reinforced polymer composites balance mechanical performance to a better extent than non-hybrid composites. The hybridisation of natural fibre-reinforced polymer composites can be a combination of natural–synthetic fibre, natural–natural fibre, natural fibre with carbonaceous materials and natural fibre with metals, as shown in Fig. 12. In general, natural fibres can be divided into two types: low-elongation (LE) and high-elongation (HE) fibres. LE fibres commonly referred to as the first fibres to fail, wheresa HE fibres display higher failure strains than LE fibres [163]. LE and HE fibres can be hybridised in many different configurations, such as interlayer (staking the fibres and it is the cheapest method) as shown in Fig. 13(a), intralayer (mixed within the fibre layers) as shown in Fig. 13(b) and intrayarn (co-mingle on fibre layers) as shown in Fig. 13(c).

Although the hybrid composites possess many advantages in terms of mechanical performance, the hybrid effect with complex load conditions, such as fatigue, quasi static and creep tests, are still not well understood. Apparent results are conflicting with regard to conclusions and mechanisms [59,164–167]. Thus, this section aims to streamline the findings of previous researchers to explore the significance of hybridising OPFs with other fibres in terms of improving mechanical behaviour. Currently, polymer composites reinforced with hybrid natural fibres, particularly OPFs, are interesting because of their low costs. However, they are difficult to manufacture because of their different characteristics and their interfacial adhesion. Thus, this section is narrowed to summarise the recent works conducted by various researchers on the mechanical properties of hybrid-OPF-reinforced polymer composites. Table 10 displays the

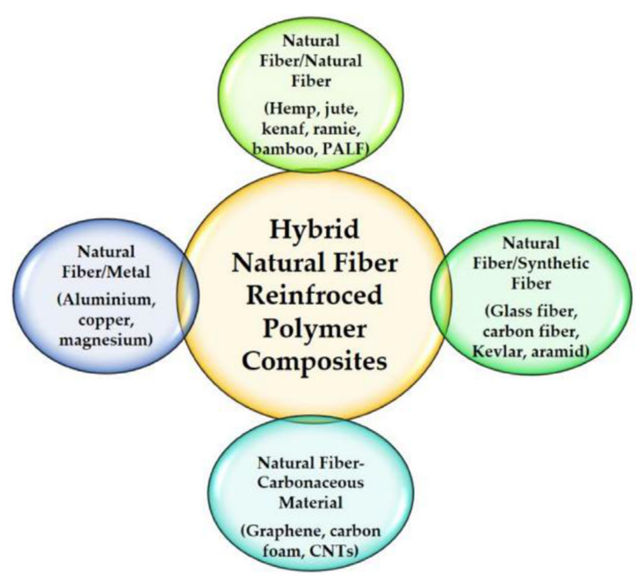

Fig. 12 – Summary of hybrid natural fibre reinforced polymer composites [21].

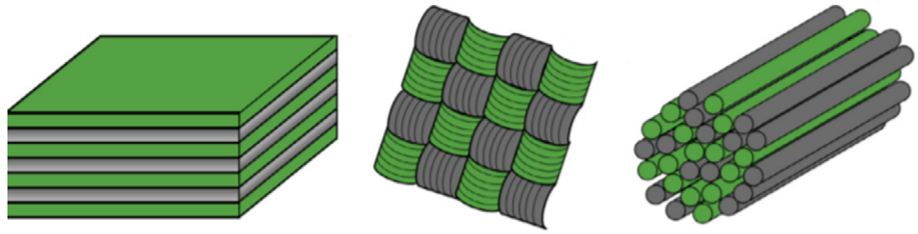
(a) (b) (c)

Fig. 13 – The three main hybrid configurations: (a) interlayer or layer-by-layer, (b) intralayer or yarn-by-yarn, and (c) intrayarn or fibre-by-fibre [163].

mechanical properties of hybrid-OPF-reinforced polymer biocomposites.

Amir et al. [128] conducted a study on the influence of layering sequence and gamma radiation on mechanical properties of epoxy composites reinforced with hybrid oil palm or Kevlar fibres. They implemented three levels of gamma radiation doses (24, 50 and 150 kGy) with two distinct layering sequences (Kevlar–oil palm–Kevlar and oil palm–Kevlar–oil palm). They highlighted that the gamma radiated on hybrid oil palm/Kevlar composites significantly improved the tensile and flexural properties. For instance, Kevlar/oil palm/Kevlar fibres composites exhibited remarkable improvements after the samples were irradiated at 25 kGy. However, the higher the intensity gamma radiation (150 kGy) significantly reduced mechanical properties. The authors revealed that tensile fracture composites exposed to abundance of voids and fibre pull-out. At the end of this work, the demonstrated that gamma radiation treatments can enhance hybrid OPF composites and that these composites are promising materials for automotive, aerospace and construction applications.

Many researches have focused on implementing hybrid natural–natural fibre composites due to their remarkable potential and cost effectiveness. Thus, several researchers had evaluated the effect of kenaf fibre loading on the mechanical properties of OPF-reinforced polymer composites. For instance, Khoshnava et al. [168] established that flexural stiffness and strength of oil palm-reinforced polyhydroxybutyrate (PHB) composites increased with kenaf bast fibre load. They deduced that 11-layer PHB biocomposites reinforced with kenaf or oil palm hybrid fibres can replace wood and woody products.

Hanan et al. [135] evaluated the mechanical performance of epoxy biocomposites containing hybrid oil palm EFB and non-woven kenaf mats. Kenaf fibres have better interfacial bonding between fibres and matrices. Kenaf fibres can withstand a high load during load transfer, thus leading to good mechanical properties. However, OPF-reinforced polymer composites absorb more energy during impact load because of the interlaced fibre bundles of oil palm. In conjunction to this study, Hanan et al. [127] evaluated same the biocomposites but containing different kenaf fibres, which were woven fabric. The same trends showed in flexural and tensile properties as the kenaf fibre load increased and a high mechanical performance were observed. Micrograph analysis results are shown in Fig. 14. The kenaf fibre exhibited lower fibre pull-out and more compact and densified fibre structure because of the higher modulus of the kenaf fibre. Mansor et al. [169] showed that the best layering sequence of epoxy biocomposites reinforced with oil palm or kenaf fibres was kenaf mat–oil palm–kenaf mat.

Jawaid et al. [170] established that jute fibre increases the tensile properties of OPF-reinforced epoxy composites. As the jute fibre loading increased, the mechanical performance of oil palm/epoxy composites due to jute fibres were able to withstand a high load, and load to the OPFs was decreased. Thus, jute/OPFs composites are potential materials that can compete with synthetic composites if properly designed.

Ramlee et al. [51] evaluated the influence of sugarcane bagasse fibre loading on OPF-reinforced phenolic composites. They established that the high OPF loading in hybrid composites showed notable tensile strength and modulus with less porous and voids area than pure composites. Oil palm composites depicted significant mechanical properties because of the high cellulosic content of OPFs whereas sugarcane bagasse decreased the water content and void in the polymer composites. Ramlee et al. [171] found that the hybridisation of silane treated with 30 wt.% of sugarcane bagasse fibres in oil palm-reinforced phenolic had improved performance in terms of tensile properties. Thus, 2 wt.% of silane-treated fibres enhanced mechanical properties, compared with 4 wt.% of hydrogen peroxide-treated fibres. They conclusively mentioned that the silane coupling agent improved interfacial bonding between the lignocellulosic fibres and matrix, indicating the improved interfacial adhesion within fibres and bio-phenolic matrix.

7. Potential application of OPF biocomposites

Oil palm is a natural fibre cultivated in Indonesia and Malaysia. As the most economical plant, many products, including food, are derived from oil palm. Oil palm has become one of the most sustainable sources of raw natural sources that are ideal sources of cellulose-based natural fibres and particles. The oil palm industry is responsible for producing huge amounts of oil palm biomass wastes in fields and oil palm mills. Despite the enormous production, the oil consists only of a small fraction of total biomass produced in the plantation, while the remainder is attributed to the huge amount of lignocellulosic materials. In general, OPFs are

Table 10 – Recent works on mechanical properties of hybrid OPFs biocomposites.

Fibre	Hybrid fibre	Matrix	Treatments/ Conditioning	Flexural		Tensile		Impact	Ref.
				Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/M^2)	
35 wt% of EFB compresed fibre mat	15 wt% Kevlar woven fabric	60 wt% of epoxy	50 kGy gamma radiation	23.6	2.813	19.1	1.6	–	[128]
3 layers of woven EFB	2 layers of woven kenaf	6 layers of poly-hydroxybutyrate	5 wt% NaOH solution for 1 h	77.9	7.3	53.3	5.4	40.6	[168]
25 wt% of EFB mat	25 wt% of non-woven kenaf fibre mats	50 wt% of epoxy	Bilayer hybrid composite configuration	113.14	7.8	50.0	3.1	1.2	[135]
15 wt% of EFB mat	35 wt% of woven kenaf fibre	50 wt% of epoxy	Bilayer hybrid composite configuration	115.8	8.7	55.7	2.97	1.78	[127]
12.55 wt% EFB short fibre	25.12 wt% kenaf mat	62.34 wt% of epoxy	Triple layer hybrid composite configuration	77.9	3.47	26.9	2.97	1.24	[169]
8 wt% of EFB fibre	32 wt% jute mat fibre	60 wt% of epoxy	Bilayer hybrid composite configuration	–	–	37.9	3.31	–	[170]
35 wt% of EFB short fibre	15 wt% sugarcane bagasse short fibre	50 wt% of phenolic	–	–	–	5.563	0.661	–	[51]
35 wt% of EFB short fibre	15 wt% sugarcane bagasse short fibre	50 wt% of phenolic	2 wt% silane solution	15.18	1.385	11.674	1.348	–	[171]
35 wt% of EFB short fibre	15 wt% sugarcane bagasse short fibre	50 wt% of phenolic	4 wt% hydrogen peroxide solution	9.33	0.903	7.471	0.935	–	

available in many forms, including pressed fruit fibres, EFB, OPT, palm kernel shell, mesocarp fibre and oil palm frond. OPT and oil palm fronds constitute the largest proportion of waste products in oil palm plantation. In general, 24% of OPF can be collected from each palm tree, and OPT accounts for 70% of replanting activities [172]. Although these fibres are considered naturally degradable, these wastes are capable to pollute the environment owing to a large amount of waste generated.

In general, oil palm biocomposites have huge potential as materials for high-performance applications. Considerable amount of effort is needed to improve the properties fo OPFs, particularly fibre modifications, hybridising with other natural fibres in synergetic approach, applying additives/enhancers in the composites and conducting suitable manufacturing process for specific applications. Oil palm biocomposites can be achieved towards high-performance applications for various sectors. Thus, the comparable mechanical properties of oil palm lignocellulosic fibre over the synthetic fibres, low production cost, good thermal and acoustic characteristics and eco-friendly processing make them a good alternative reinforcement materials in polymer composites. Figure 15 shows the applications of OPF biocomposites.

Over the past decades, the development of natural fibre-reinforced polymer composites has been reported, and these composites have been widely used in many industries manufacturing various types of products, including automotive components [173–175], biodegradable packaging materials [176] and building and structural materials [21]. In addition, oil palm biomass is used in the production of high-performance materials, such as bulletproof and ballistic applications [177], thermal insulators, concrete ingredient in the building industry, carbon activation for water treatment and automobile disk brake pads [131,178]. Moreover, oil palm biomass waste has been utilised for the production of various types of value-added products such as medium density fibre (MDF), blockboard, laminated veneer lumber (LVL), oriented strand board (OSB), particleboard, plywood, chipboard, hardboard, thermoset and thermoplastic composites, nano-biocomposites and pulp and paper manufacturing [43,179]. These products can be industrially produced as the primary raw material in furniture manufacturing. OPT is one of the mostly utilised oil palm biomass in the furniture industry as the alternative material for manufacturing wood furniture. OPT replaces or reinforces rubberwood and other solid species attributed to its comparable quality in terms of physical and mechanical properties, thermal stability and high resistance to pests, such as termites. Furniture products partly composed of oil palm biomass include tables, chairs, doors, flooring and cabinetry. To date, ongoing research still has been done by global research institutions, such as SCION (New Zealand), Biocomposites Centre (UK), CSIRO

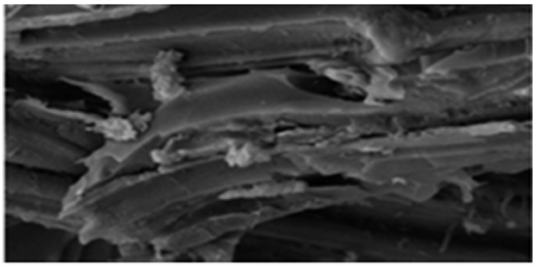

Fig. 14 – SEM micrograph of 35 wt% of kenaf fibre hybridized with 15 wt% of oil plam fibre reinforced epoxy composites [127].

(Australia), Forest Product Laboratory (USA) and various Malaysian and Indonesian research universities to improve the application of oil palm biomass and socioeconomics of local farmers [180]. Hashim et al. [181], Radzi et al. [182] and Sahari et al. [183] studied the effects of particle size, geometry, type and composition of OPFs from OPT and EFB, respectively, on the mechanical and physical properties of green biocomposites. The study on the effect of matrix or resin used to produce biocomposites that comply with the Japanese Industrial Standard and European Standard evaluated the biocomposites and evaluated their suitability as materials for furniture products and suit for building components [184,185].

In 2002, the Indonesian government had introduced a construction scheme in the RSH affordable house program that used palm oil fibre waste to replace the conventional wood in most of the components, such as roof structures, wall frames, wall covers, doors and windows (Fig. 16). This initiative is as an effort to elevate the utilisation of biomass waste particularly oil palm waste for value-added applications such as building construction components [186].

Particleboards and fibreboard (HDF and MDF) from OPF are commonly utilised for building components. However, these materials are not meant for exterior usage due to excessive outdoor weather. Therefore, to meet the requirement of the application, this perspective has been overcome through various types of hybridisation and chemical modifications to keep the lignocellulosic-based material away from the vulnerable effect of weather [186]. For example, Abdul Khalil et al. [187] demonstrated the application of phenol-based resins incorporated with OPFs in the form of OPT and EFB. They showed that biocomposites can be produced for exterior needs. Nuryawan et al. [130] improved the properties of OPT/EFB hybrid plywood by adding OPA nanoparticles and PF resin as a binder. Good mechanical and thermal properties of the hybrid composites plywood proved that they can be used in outdoor applications and building components.

In addition, other than the mechanical and thermal stability of the composites, oil palm composites were studied for

Fig. 15 – Diversity of applications of OPF biocomposites.

flame-retardant materials suitable for advanced applications such as building materials, as well as for other functions that required high-end products, including aerospace and automotive parts. The effects of flammability properties of oil palm-based composites were studied by Suriani et al. [124], who used incorporated OPFs into magnesium hydroxide ($Mg(OH)_2$) in epoxy polymer and polyester yarn. The flammability properties of the hybrid composites were determined with a horizontal burning test. The specimen with 20% of EFB fibre had the lowest burning rate of 11.47 mm/min. The other specimen with fibre addition of 35% and 50% had burning rates of 14.38 and 17.30 mm/min, respectively. OPF was studied for hybridised flame-retardant formulations containing carbon black (CB) and Arabic gum (GAP) incorporated in polyester composites (OPFPC) panels. Suoware and Edelugo [188] fabricate various formulations of OPFPC hybrid panels through hand lay-up compression moulding techniques with the addition of flame retardant fillers (aluminium hydroxide [ATH] and ammonium polyphosphate [APP]) to analyse the effect of flame retardency properties. Through thermal analysis, the optimum properties have been reported for 12% ATH and 15% APP loading in GAP/CB hybrid composite panel. The mechanism of flame retardency mainly attributed to the addition of flame-retardant filler ATH, which was dehydrated endothermically upon heating, and the presence of CB in APP–GAP restricted the mobility of the polyester resin. The inclusion of flame retardant filler improved the char residue at the end of TGA test with the highest formation of char were observed for 15% APP–GAP/CB formulation which suggested for better flammability properties.

Oil palm biomass waste was analysed in thermal insulation materials used in the building sector. Ramlee et al. [189] reviewed the OPF-reinforced composites in terms of thermal, acoustic, physical and mechanical performance of the biomass-based composites as an efficient thermal insulator, which significantly reduces the excess utilisation of energy and cost. This finding was supported by the study of Agrawal et al. [190], who analysed the effect of palm fibre-reinforced binary phenol-formaldehyde composites on the thermal conductivity and thermal diffusivity properties. The author found the thermal conductivity and diffusivity of the composites decreased as the amount of fibre increased in the composite system. The experimental conductivity behaviour of the OPF was 0.24 W/(m.K), which was lower than that pure PF (0.348 W/[m.K]). Meanwhile, Samsudin et al. [191] reported the optimum sound absorption coefficient of 18 mm -hick powder OPF samples at a low frequency (1500 Hz) was 0.60, whilst at the high frequency of 3750 Hz was 0.99. This result indicated that thick OPFs can absorb more sound energy than thin samples (6 and 12 mm).

The applications of oil palm biomass also used to be added to the composites to achieve good biodegradable properties. Biodegradability properties are very important especially for bio-based packaging materials as one of the solutions to overcome the plastic waste problem caused by synthetic materials. The ability of OPF-reinforced polymer composites to decompose in the environment has been widely studied. Indrayani et al. [192] incorporated OPF into a PLA polymer matrix. They found that increasing the amount of cellulose fibre extracted from OPF in PLA accelerated the decomposition process. The high percentage of weight loss occurred in the

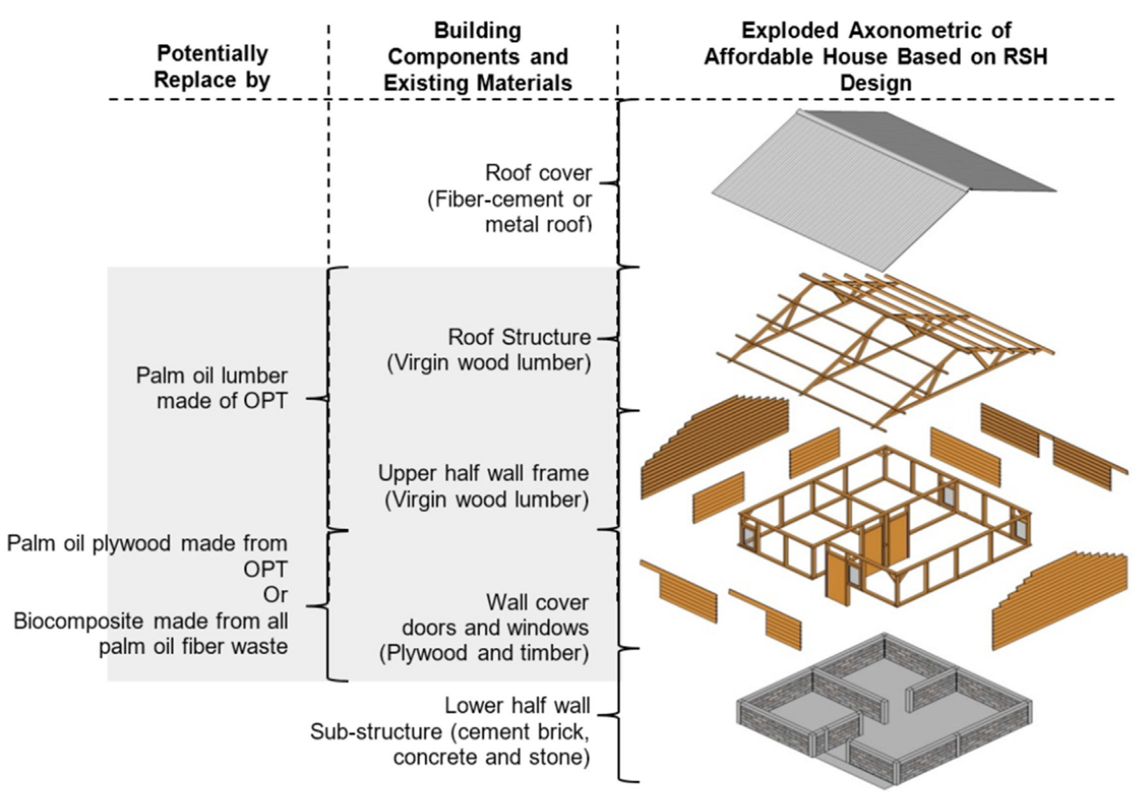

Fig. 16 – Indonesia's construction scheme in the RSH affordable house program [186].

composites with 20 phr cellulose OPF, and the weight loss percentage was 0.5359%, which is higher than that found in control sample (0.0857%). Abdul Khalil et al. [176] used oil palm shell (OPS) nanofillers in seaweed-based composite films to improve the mechanical, physical and morphological properties of the materials. The addition of OPS at a high concentration of 20% w/w showed the optimum tensile strength (44.8 MPa) and Young's modulus (3.13 GPa). However, the high loading of OPS filler led to the decrement of the film's hydrophobicity and lowered its contact angles (47.3°). Moreover, OPF was studied in the preparation of film adsorbents for water treatment applications. The study was done by Rahmi et al. [193], who used oil palm empty fruit bunch-based charcoal and chitosan and incorporated them into an EDTA matrix to form an absorbent film through a simple phase inversion technique for Cd (II) removal. Cadmium pollution is usually detected in water sources located near high industrial activities. The removal of cadmium and other heavy metals found in water sources, especially rivers, is essential to the protection of the environment and human health. According to the study, OC/Chi–EDTA film had a maximum absorption capacity of 283.33 mg/g according to the Langmuir isotherm model. In the adsorption mechanism, the electrostatic attraction and complexation were responsible for the Cd (II) uptake, with an adsorption capacity of 67.2 mg/g and removal efficiency of 99.56%. Meanwhile, the regeneration study suggested that OC/Chi–EDTA films can be used to up to four cycles, and the removal efficiency can exceed 75%. These findings indicated the capability of OC/Chi–EDTA film as a film adsorbent with a high Cd (II) uptake.

8. Conclusion and future perspective

The stringent environmental regulations and the quest towards sustainable materials have led researchers towards the development of eco-friendly materials. OPF waste is the strongest waste generated by the palm oil industry, accounting for approximately 22%–23% of total processed fresh fruit. Consequently, this phenomena would results in several tonnes of fibrous waste mass, known commonly as oil palm empty fruit bunch-per hectare of the plantation. When the waste materials are inappropriately disposed such as left in fields, they can pose severe environmental problems, such as fouling and pests. Thus, novel methods for recycling and using the OPFs as materials in products, particularly fibres found on the OPF, are necessary. An advancement in utilizing OPF-reinforced polymer composites with good mechanical properties have potential applications in the modern industry in general and the high pressurized vessel [194] and civil infrastructure sector [195] in particular. OPF-reinforced thermoset and thermoplastic composites possess tensile and flexural properties and impact strength. The enhancement of the properties of OPF biocomposites can be achieved by subjecting the fibres to chemical and thermal modification treatments and adding additives, such as organic nanosilica. A synergetic approach in hybridising OPF with suitable hybrid fibres in optimal sequence and orientation results in composites with high performance. The implementation of OPFs as secondary constituents or additives in primary strong fibres, such as kenaf bast and flax fibre, would result positive output in terms of mechanical performance. Thus, the comparable mechanical properties of oil palm lignocellulosic fibre over the synthetic fibres, low production cost, good thermal and acoustic characteristics and eco-friendly processing make them good alternative reinforcement materials for polymer composites.

This review article is expected to provide a collective facts and information to promote further investigations on other natural fibre composites, such as jute, kenaf, flax and sugarcane fibres. Moreover, the issues of thermal stability and the moisture absorption are suggested to be addressed to widen the application range of OPF biocomposites. The future work will focus on the production of green composites and nanocomposites from oil palm and using natural-based resin polymers with enhanced mechanical performance for sustainable materials and productions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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